

A QUANTITATIVE ANALYSIS OF THE RESPONDING MAINTAINED BY INTERVAL SCHEDULES OF REINFORCEMENT¹

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Interval schedules of reinforcement maintained pigeons' key-pecking in six experiments. Each schedule was specified in terms of mean interval, which determined the maximum rate of reinforcement possible, and distribution of intervals, which ranged from many-valued (variable-interval) to single-valued (fixed-interval). In Exp. 1, the relative durations of a sequence of intervals from an arithmetic progression were held constant while the mean interval was varied. Rate of responding was a monotonically increasing, negatively accelerated function of rate of reinforcement over a range from 8.4 to 300 reinforcements per hour. The rate of responding also increased as time passed within the individual intervals of a given schedule. In Exp. 2 and 3, several variable-interval schedules made up of different sequences of intervals were examined. In each schedule, the rate of responding at a particular time within an interval was shown to depend at least in part on the local rate of reinforcement at that time, derived from a measure of the probability of reinforcement at that time and the proximity of potential reinforcements at other times. The functional relationship between rate of responding and rate of reinforcement at different times within the intervals of a single schedule was similar to that obtained across different schedules in Exp. 1. Experiments 4, 5, and 6 examined fixed-interval and two-valued (mixed fixed-interval fixed-interval) schedules, and demonstrated that reinforcement at one time in an interval had substantial effects on responding maintained at other times. It was concluded that the rate of responding maintained by a given interval schedule depends not on the overall rate of reinforcement provided but rather on the summation of different local effects of reinforcement at different times within intervals.

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The statement that responses take place in time expresses a fundamental characteristic of behavior (Skinner, 1938, pp. 263-264). Responses occur at different rates, in different se-

¹This research was supported by NSF Grants G8621 and G18167 (B. F. Skinner, Principal Investigator) to Harvard University, and was conducted at the Harvard Psychological Laboratories. Some of the material has been presented at the 1961 and 1963 meetings of the Psychonomic Society. The authors' thanks go to Mrs. Antoinette C. Papp and Mr. Wallace R. Brown, Jr., for care of pigeons and assistance in the daily conduct of the experiments, and to Mrs. Geraldine Hansen for typing several revisions of the manuscript. We are indebted to many colleagues, and in particular to N. H. Azrin, who maintained responsibility for the manuscript well beyond the expiration of his editorial term, and to D. G. Anger, L. R. Gollub, and S. S. Pliskoff. Some expenses of preparation of the manuscript were defrayed by NSF Grant GB 3614 (to New York University), by NSF Grants GB 316 and GB 2541 (to the University of Chicago), and by the Smith Kline and French Laboratories. Expenses of publication were defrayed by NIH Grant MH 13613 (to New York University) and NSF Grants GB 5064 and GB 6821 (to the University of California, San Diego). Reprints may be obtained from A. C. Catania, Department of Psychology, New York University, University College of Arts and Sciences, New York, N.Y. 10453.

quences, and with different temporal patterns, depending on the temporal relations between the responses and other events. One event of fundamental interest is reinforcement, and the rate at which responses occur and the changes in this rate over time are strongly determined by the schedule according to which particular responses are reinforced (*e.g.*, Morse, 1966).

An interval schedule arranges reinforcement for the first response that occurs after a specified time has elapsed since the occurrence of a preceding reinforcement or some other environmental event (Ferster and Skinner, 1957). In such a schedule, the spacing of reinforcements in time remains roughly constant over a wide range of rates of responding. The schedule specifies certain minimum intervals between two reinforcements; the actual durations of these intervals are determined by the time elapsed between the availability of reinforcement, at the end of the interval, and the occurrence of the next response, which is reinforced. The patterns and rates of responding maintained by interval schedules usually are such that this time is short relative to the durations of the intervals.

Ferster and Skinner (1957, Ch. 5 and 6) have described in considerable detail some important features of the performances maintained by interval schedules. In a fixed-interval (FI) schedule, the first response after a fixed elapsed time is reinforced, and an organism typically responds little or not at all just after reinforcement, although responding increases later in the interval. In a variable-interval (VI) schedule, the first response after a variable elapsed time is reinforced, and a relatively constant rate of responding is maintained throughout each interval. Detailed examination shows, however, that this responding may be modulated by the particular durations of the different intervals that constitute the schedule. In other words, the distribution of responses in time depends on the distribution of reinforcements in time. For example, responding shortly after reinforcement increases with increases in the relative frequency of short intervals in the schedule (Ferster and Skinner, 1957, p. 331-332). Thus, it is important to study not only the rate of responding averaged over the total time in an interval schedule, but also the changes in the rate of responding as time passes within indi-

vidual intervals. (The former, a rate calculated over the total time in all the intervals of a schedule, will be referred to as an *overall* rate; the latter, a rate calculated over a period of time that is short relative to the average interval between reinforcements, will be referred to as a *local* rate. The terms will be applied to reinforcement as well as to responding. The terminology has the advantage of pointing out that both reinforcement and responding are measured in terms of events per unit of time.)

In a VI schedule, a response at a given time after reinforcement is reinforced in some intervals but not in others. The probability of reinforcement at this time is determined by the relative frequency of reinforcement at this time, which may be derived from the distribution of intervals in the schedule. The distribution of intervals in a VI schedule may act upon behavior because the time elapsed since a preceding reinforcement (or since any other event that starts an interval) may function as a discriminable continuum. Skinner (1938, p. 263 *ff.*), in his discussion of temporal discrimination, included the discrimination of the time elapsed since reinforcement as a factor in his account of the performances maintained by FI schedules. The major difference between FI and VI schedules is that an FI schedule provides reinforcement at a fixed point along the temporal continuum, whereas a VI schedule provides reinforcement at several points. The present account analyzes performances maintained by different interval schedules in terms of the local effects of different probabilities of reinforcement on the local rates of responding at different times.

Within interval schedules, reinforcement may be studied as an input that determines a subsequent output of responses (*cf.* Skinner, 1938, p. 130). In this sense, the study of the performances maintained by interval schedules is a study of response strength. The concept of response strength, once a reference to an inferred response tendency or state, has evolved to a simpler usage: it is "used to designate probability or rate of responding" (Ferster and Skinner, 1957, p. 733). This evolution is a result of several related findings: that the schedule of reinforcement is a primary determinant of performance; that different measures of responding such as rate and resistance to extinction are not necessarily

highly correlated; that rate of responding is relatively insensitive to such variables as amount of reinforcement and deprivation; that rate of responding is itself a property of responding that can be differentially reinforced; and that rate of responding can be reduced to component interresponse times (e.g., Anger, 1956; Ferster and Skinner, 1957; Herrnstein, 1961; Skinner, 1938). Nevertheless, the relationship between reinforcement and responding remains of fundamental importance to the analysis of behavior. Many studies of response strength have been concerned with the acquisition of behavior (learning: e.g., Hull, 1943) or with the relative strengths of two or more responses (choice: e.g., Herrnstein, 1961). The present experiments emphasize reinforcement as it determines performance during maintained or steady-state responding, rather than during acquisition, extinction, and other transition states, and are concerned with absolute strength, rather than with strength relative to other behavior.

EXPERIMENT 1: RATE OF RESPONDING AS A FUNCTION OF RATE OF REINFORCEMENT IN VARIABLE-INTERVAL SCHEDULES

The relation between the overall rate of reinforcement and the overall rate of a pigeon's key-pecking maintained by interval schedules may be thought of as an input-output function for the pigeon. In Exp. 1, this function was determined for VI schedules over a range of overall rates of reinforcement from 8.4 to 300 rft/hr (reinforcements per hour). Each schedule consisted of an arithmetic series of 15 intervals ranging from zero to twice the average value of the schedule and arranged in an irregular order. Thus, the relative durations of the particular intervals that made up each schedule were held constant.

METHOD

Subjects and Apparatus

The key-pecking of each of six adult, male, White Carneaux pigeons, maintained at 80% of free-feeding body weights, had been rein-

forced on VI schedules for at least 50 hr before the present experiments.

The experimental chamber was similar to that described by Ferster and Skinner (1957). Mounted on one wall was a translucent Plexiglas response key, 2 cm in diameter and operated by a minimum force of about 15 g. The key was transilluminated by two yellow 6-w lamps. Two white 6-w lamps mounted on the chamber ceiling provided general illumination. The operation of the key occasionally produced the reinforcer, 4-sec access to mixed grain in a standard feeder located behind a 6.5-cm square opening beneath the key. During reinforcement, the feeder was illuminated and the other lights were turned off.

Electromechanical controlling and recording apparatus was located in a separate room. A device that advanced a loop of punched tape a constant distance with each operation (ratio programmer, R. Gerbrands Co.) was stepped by an electronic timer, and intervals between reinforcements were determined by the spacing of the holes punched in the tape. Thus, the absolute durations of the intervals depended on the rate at which the timer operated the programmer, but the relative durations were independent of the timer.

The punched holes in the tape provided a series of 15 intervals from an arithmetic progression, in the following order: 14, 8, 11, 6, 5, 9, 2, 13, 7, 1, 12, 4, 10, 0, 3. The numbers indicate the durations of the intervals between successive reinforcements in multiples of t sec, the setting of the electronic timer. (To permit the arrangement of a 0-sec interval, in which reinforcement was available for the first peck after a preceding reinforcement, the ratio programmer was stepped at each reinforcement as well as at the rate determined by the electronic timer.) In this series, the average interval of the VI schedule was 7 t sec; with t equal to 6.5 sec, for example, the average interval was 45.5 sec.

At the end of each interval, when a peck was to be reinforced, the controlling apparatus stopped until the peck occurred; the next interval began only at the end of the 4-sec reinforcement. Thus, the apparatus arranged a distribution of minimum interreinforcement intervals; the actual intervals were given by the time from one reinforcement to the next reinforced response. In practice, the

rates of responding at most VI values were such that differences between the minimum and the actual interreinforcement intervals were negligible.

Stepping switches that stepped with each step of the ratio programmer and that reset after each reinforcement distributed key-pecks to the 14 counters, which represented successive periods of time after reinforcement. The time represented by each counter was t sec, and each counter recorded responses only within interreinforcement intervals equal to or longer than the time after reinforcement that the counter represented. For example, the first counter cumulated responses that occurred during the first t sec of all intervals except the 0-sec interval (the 0-sec interval was terminated by a single reinforced response). Correspondingly, the seventh counter cumulated responses during the seventh t sec of only those intervals $7t$ sec long or longer. The fourteenth counter cumulated responses only during the fourteenth t sec of the $14t$ -sec interval, the longest interval in the series. Thus, response rates at early times after reinforcement were based on larger samples of pecking than response rates at later times.

Procedure

Seven VI schedules with average intervals ranging from 12.0 to 427 sec (300 to 8.4 rft/hr) were examined. Each pigeon was exposed to VI 12.0-sec, VI 23.5-sec, and VI 45.5-sec, and to a sample of the longer average intervals, as indicated in Table 1. (Occasional sessions in which equipment failed have been omitted; none were within the last five sessions of a given schedule.) Each schedule was in effect

for at least 15 daily sessions and until the pigeon's performance was stable, as judged by visual inspection of numerical data and cumulative records, for five successive sessions. With few exceptions, the rate of responding in each of the last five sessions of a given schedule was within 10% of the average rate over those sessions.

The first peck in each session was reinforced and the VI schedule then operated, beginning at a different place in the series of intervals in successive sessions. Thus, each scheduled interval, including the first in the session, began after a reinforcement. Sessions ended after each interval in the series had occurred four times (61 reinforcements). Thus, the duration of a session ranged from about 16 min (12 min of VI 12-sec plus 61 reinforcements) to about 431 min (427 min of VI 427-sec plus 61 reinforcements).

RESULTS

The overall rate of key-pecking as a function of the overall rate of reinforcement is shown for each pigeon in Fig. 1. The functions were, to a first approximation, monotonically increasing and negatively accelerated, perhaps approaching an asymptotic level for some pigeons. With increasing rates of reinforcement, the rate of responding increased more rapidly at low rates of reinforcement (for most pigeons, to roughly 50 rft/hr) than at higher rates of reinforcement. The shapes of the functions differed in detail from pigeon to pigeon: Pigeon 118, for example, produced a fairly smooth increasing function; Pigeon 121, an almost linear function; and Pigeons 278 and 279, a rapid increase to a near invariance in the rate of re-

Table 1

Mean intervals (sec) of the arithmetic variable-interval schedules arranged for each pigeon, with number of sessions for each schedule shown in parentheses.

Pigeon					
118	121	129	278	279	281
108 (52)	45.5 (52)	108 (29)	23.5 (35)	427 (52)	23.5 (35)
45.5 (29)	23.5 (29)	216 (35)	12.0 (17)	216 (29)	45.5 (17)
23.5 (22)	12.0 (58)	427 (29)	45.5 (29)	108 (22)	12.0 (29)
12.0 (36)	108 (22)	23.5 (22)	216 (22)	23.5 (36)	427 (58)
323 (37)	23.5 (15)	45.5 (36)	108 (36)	12.0 (22)	45.5 (22)
108 (28)		12.0 (22)	45.5 (22)	45.5 (15)	12.0 (43)
		23.5 (15)	427 (15)	108 (29)	
		108 (28)	427* (26)		

*Reinstated after interruption.

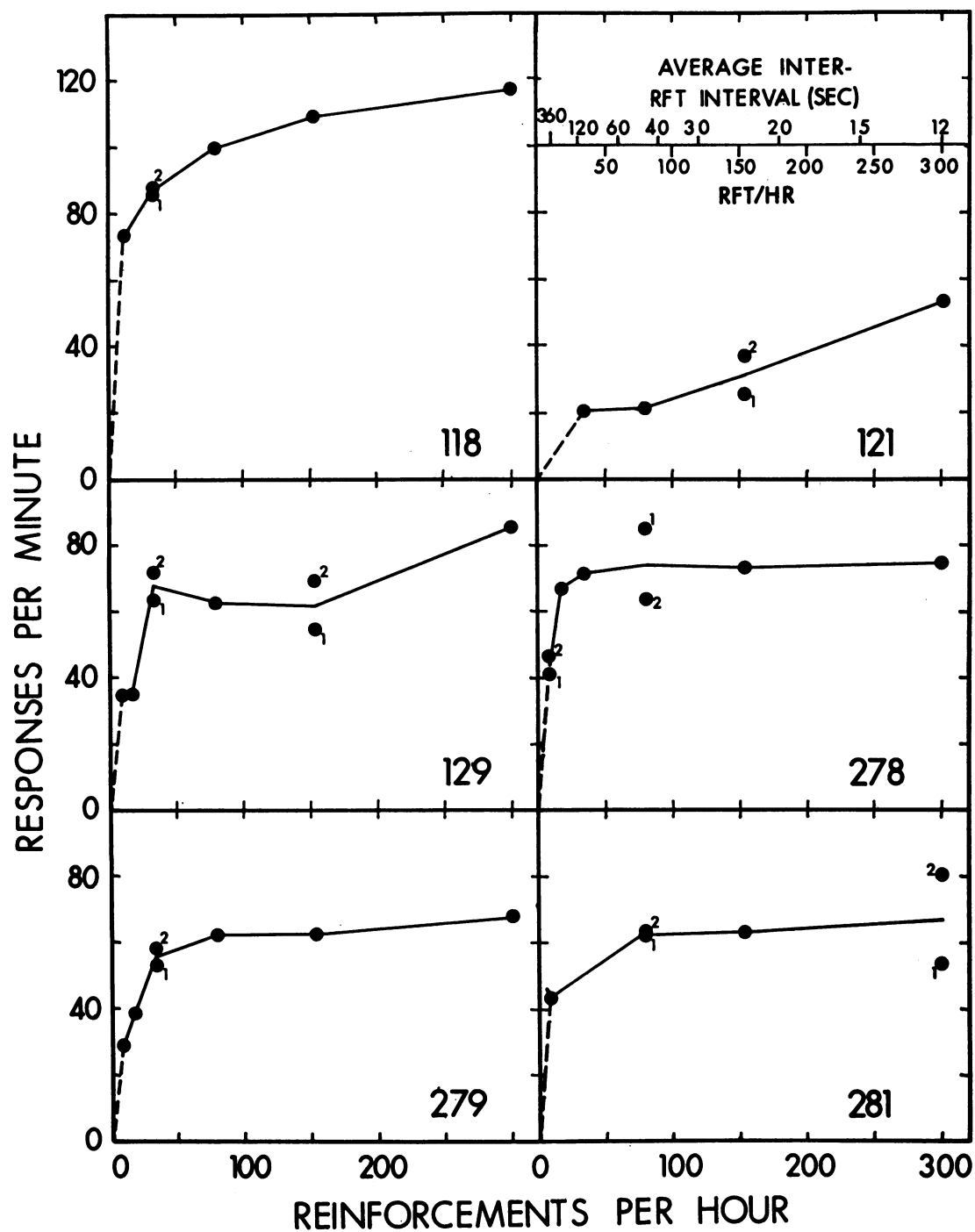


Fig. 1. Rate of key-pecking as a function of rate of reinforcement for six pigeons. Key-pecking was maintained by VI schedules consisting of 15 intervals in an arithmetic progression of size, but arranged in an irregular order. Each point is the arithmetic mean of the rates of responding over the last five sessions of a given schedule. Numerals 1 and 2 indicate first and second determinations. Some representative average interreinforcement intervals, proportional to reciprocals of the rates of reinforcement (rft/hr), are shown on the scale at the upper right.

sponding. This near invariance might be called a "locked rate" (Herrnstein, 1955; Sidman, 1960), a term that has been applied to the occasionally observed insensitivity of a given pigeon's rate of responding to changes in the parameters of an interval schedule of reinforcement.

Despite the near invariance, the functions appear in general to increase over their entire range. (Reversals, as for Pigeon 129 at 33.3 rft/hr, were within the limits of variability implied by the redeterminations, which generally produced higher rates of responding than the original determinations.) The average rate of responding maintained by 300 rft/hr was higher than that maintained by 153 rft/hr for all pigeons. In addition, rates of responding at higher rates of reinforcement may be spuriously low, because the contribution of the latency of the first response after reinforcement to the overall rate of responding was greatest at the higher rates of reinforcement. A correction for this latency would slightly increase rates of responding at the higher rates of reinforcement (300, 153, and, perhaps, 79 rft/hr), but would have virtually no effect at the lower rates of reinforcement. Despite the small changes at high rates of reinforcement, it seems reasonable to conclude that overall rates of responding increase monotonically (perhaps approaching an asymptote) as overall rate of reinforcement increases.

Within individual intervals between two reinforcements, the rate of key-pecking increased with increasing time since reinforcement, as shown for each pigeon in Fig. 2, which plots local rates of responding against the absolute time elapsed since reinforcement. The functions reflect in their vertical separation the different overall rates maintained by each schedule (Fig. 1).

Data obtained with each arithmetic VI schedule for each pigeon are plotted against relative time since reinforcement in Fig. 3. The functions have been adjusted by multiplying local rates of responding by constants chosen to make the average rate of responding for each function equal to 1.0. When the differences in overall levels of the functions were removed by this adjustment, the local rate of responding within intervals grew as approximately the same function of relative time after reinforcement in most VI sched-

ules studied with most pigeons. The major exceptions were some pigeons' data from the shorter VI schedules: Pigeon 121 at 12.0 and 23.5 sec; Pigeon 278 at 23.5 and 45.5 sec; and Pigeon 281 at 12.0 sec. It may be relevant that only in these schedules were rates of responding sometimes low enough to produce large differences between the minimum and actual interreinforcement intervals. For the remaining functions, there appeared to be no systematic ordering from one pigeon to another of the slopes or degrees of curvature of the several functions (see, however, Exp. 3, Discussion).

As with overall rates of responding (Fig. 1), the functions differed in detail from pigeon to pigeon, even if the atypical data from the shorter VI schedules are ignored. For a given pigeon, however, the functions in Fig. 1 and in Fig. 3 were generally similar: fairly smooth increasing functions for Pigeon 118, almost linear functions for Pigeon 121 except for data from the shorter VI schedules, and rapid increases to a near invariance for Pigeons 278 and 279. The similarity is debatable for Pigeon 281 even when the 12.0-sec function is disregarded, and no simple relationship is evident between the two sets of data for Pigeon 129. The possible significance of the similarities is that the same variables may have operated to produce changes in both the local rate of responding, as time passed within interreinforcement intervals, and in the overall rate of responding, when the overall rate of reinforcement was changed.

A cumulative record of the responding of Pigeon 118 is shown in Fig. 4. Upward concavity, which indicates an increasing rate of responding, is evident in almost every interval between reinforcements. The averaging of rates of responding across intervals assumed that there was no systematic change in the responding within intervals from one interval to another. No consistent sequential effects were evident in the cumulative records; if present, they constituted a relatively minor effect that, for the present purposes, will be ignored.

DISCUSSION

Overall rates of responding. Individual differences among pigeons were considerable, but the functions relating overall rate of responding to overall rate of reinforcement

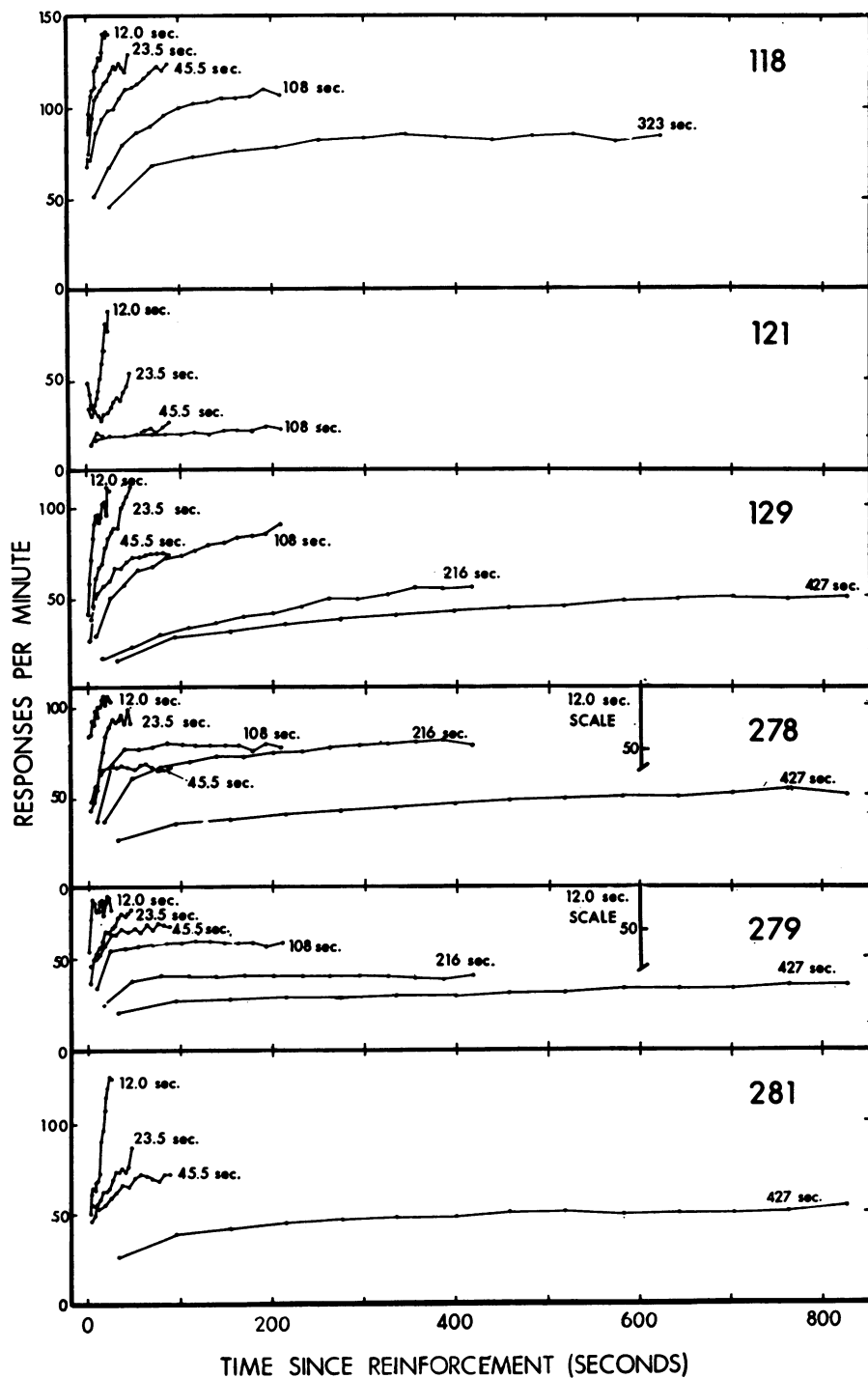


Fig. 2. Rate of key-pecking as a function of time since reinforcement in several arithmetic VI schedules. The function for each schedule, composed of averages of the local rates of responding over the last five sessions of the schedule, is identified by the mean interreinforcement interval. Two of the 12.0-sec functions have been displaced on the ordinate, as indicated by the inserted scales (Pigeons 278 and 279). For those schedules arranged twice for a given pigeon, only one function, chosen on the basis of convenience of presentation, has been plotted.

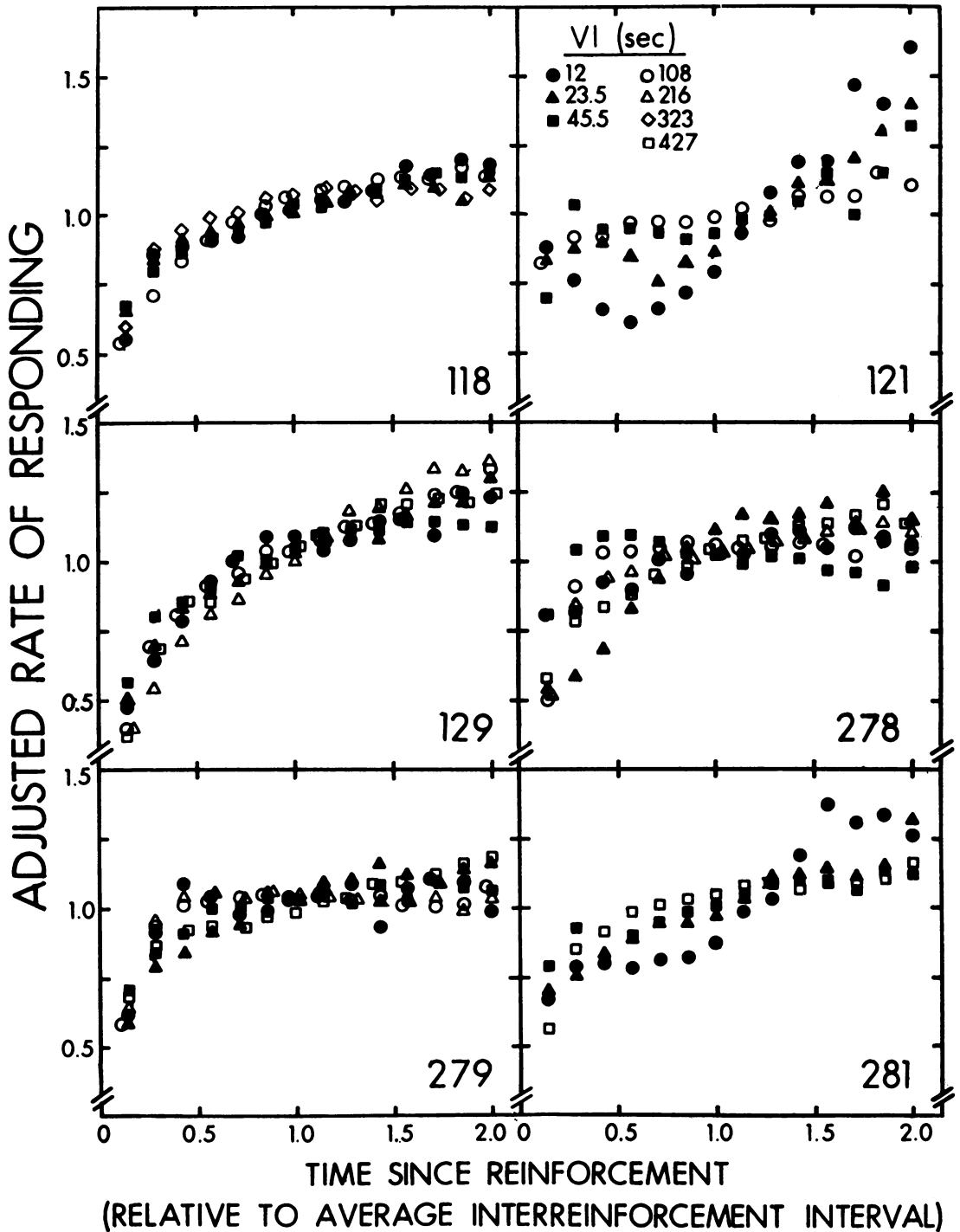


Fig. 3. Rate of key-pecking, adjusted so that the average rate of pecking equals 1.0, as a function of relative time since reinforcement in several arithmetic VI schedules. For those schedules arranged twice for a given pigeon, only the first determination has been plotted.

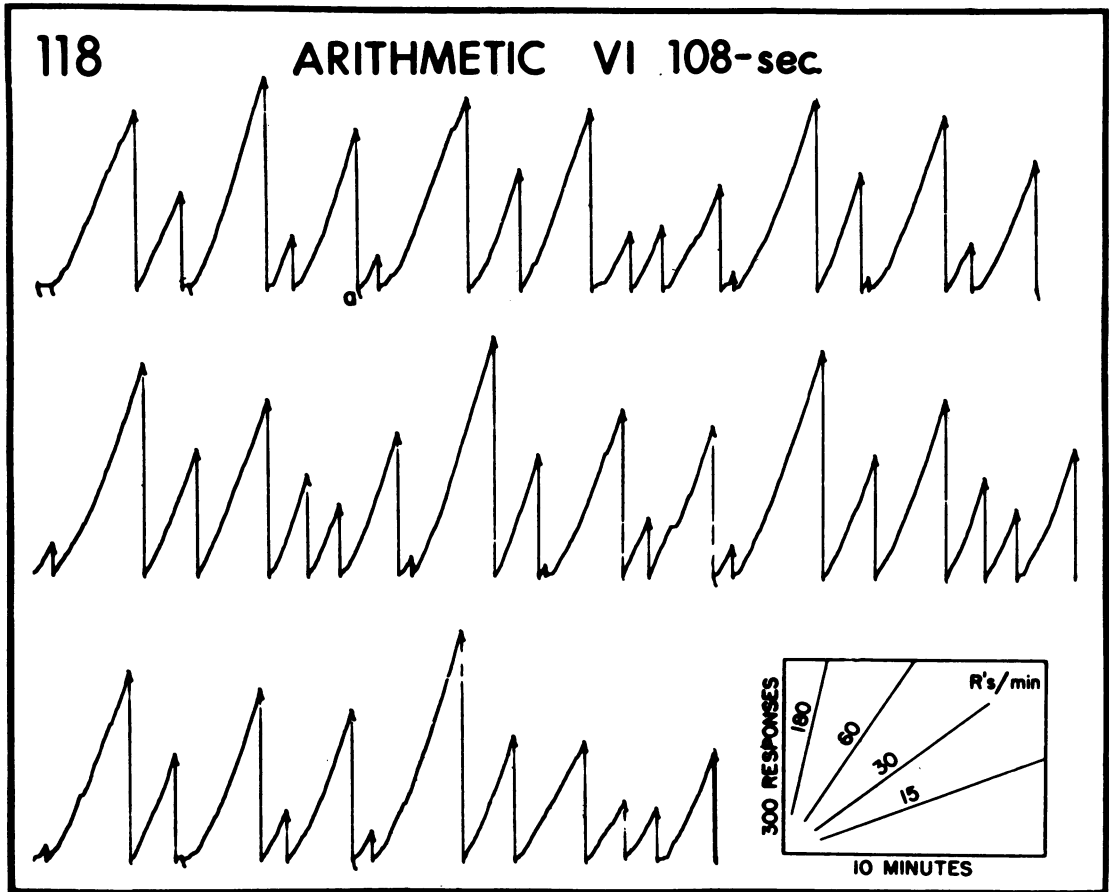


Fig. 4. Cumulative record of a full session of key-pecking maintained by an arithmetic VI schedule with a mean interreinforcement interval of 108-sec (Pigeon 118). The recording pen reset to baseline after each reinforcement, indicated by diagonal pips as at *a*, a reinforcement after a zero-sec interval. Curvature can be seen most easily by foreshortening the figure.

were generally monotonically increasing and negatively accelerated. The general nature of this relationship is well supported by the literature on both VI and FI schedules. Both pigeons and rats have been studied in a variety of experimental contexts, usually over a narrower range of rates of reinforcement than was studied here. Monotonically increasing and negatively accelerated functions have been obtained from rats by Skinner (1936; data obtained early in the acquisition of FI performance), Wilson (1954; FI schedules), Clark (1958; VI schedules at several levels of deprivation), and Sherman (1959; FI schedules). The same relationship may hold for schedules of negative reinforcement (Kaplan, 1952; FI schedules of escape). Similar functions have been obtained from pigeons by Schoenfeld and Cumming (1960) and by

Farmer (1963), whose data are discussed later (General Discussion). Other data have been obtained from pigeons by Cumming (1955) and by Ferster and Skinner (1957). In Cumming's experiment, rates of responding did not increase monotonically with rates of reinforcement, but rates of responding may not have reached asymptotic levels and the VI schedules alternated with a stimulus-correlated period of extinction. Ferster and Skinner presented data in the form of cumulative records selected to show detailed characteristics of responding; the data therefore were not necessarily representative of the overall rates of responding maintained by each schedule.

Monotonically increasing and negatively accelerated functions relating total responding to total reinforcement in concurrent schedules (Findley, 1958; Herrnstein, 1961;

Catania, 1963a), in which VI schedules were independently arranged for pigeons' pecks on two different keys, have been discussed by Catania (1963a). Additional data are provided by experiments with chained schedules (Autor, 1960; Findley, 1962; Nevin, 1964; Herrnstein, 1964), in which reinforcement of responding in the presence of one stimulus consists of the onset of another stimulus in the presence of which another schedule of reinforcement is arranged (*cf.* the review by Kelleher and Gollub, 1962).

Evidence for substantial individual differences among pigeons has been noted in the literature. Herrnstein (1955), for example, varied the overall rate of reinforcement provided by VI schedules in an experiment concerned with the effect of stimuli preceding a period of timeout from VI reinforcement. Monotonically increasing, negatively accelerated functions were obtained from two pigeons (S1, 6 to 120 rft/hr, and S3, 6 to 60 rft/hr), but the third pigeon's rate of responding was roughly constant over the range of reinforcement rates studied (S2, 6 to 40 rft/hr: this pigeon provided the basis for a discussion of "locked rate"). Individual differences among pigeons were also observed by Reynolds (1961, 1963), who obtained monotonically increasing, negatively accelerated functions when different VI schedules in the presence of one stimulus were alternated with a constant VI schedule in the presence of a second stimulus (multiple schedules).

The derivation of a mathematical function describing the relationship between reinforcement and responding for all pigeons is complicated by the idiosyncratic character of each pigeon's data, particularly if the functions are restricted to those involving simple transformations of the ordinate and/or abscissa and are limited in the number of arbitrary constants. In an earlier version of this paper (Reynolds and Catania, 1961; Catania and Reynolds, 1963), a power function was proposed, on the basis of a fit to average data for the group of pigeons (see also Catania, 1963a). This function, of the form: $R = kr^{0.2}$, where R is rate of responding, r is rate of reinforcement, and k is a constant depending on the units of measurement, was chosen in preference to a logarithmic function, of the form: $R = k \log r + n$, where n is a constant and the other symbols are as above. The

choice between these two functions was based more on logical considerations, *i.e.*, that rate of responding should approach zero as rate of reinforcement approaches zero, than on the superiority of the fit of the power function to the data. This mathematical representation, however, does not provide an adequate fit to the data from individual pigeons. Fits to data from individual pigeons are possible (*cf.* Norman, 1966), but they are not essential for the present purposes and will not be considered further here.

Local rates of responding. It has been noted (Results) that the idiosyncratic characteristics of the present data from each pigeon were reflected, to some extent, in the changes in the local rate of responding with the passage of time since reinforcement. This relationship is not mathematically determined; a given overall rate of responding could have been produced by a variety of different temporal distributions of responses within the intervals of a given schedule. Aside from a few atypical functions at high rates of reinforcement, local rates of responding generally increased monotonically as time passed since reinforcement (Fig. 3). For a given pigeon, the adjusted local rates of responding at different relative times after reinforcement remained roughly invariant over a wide range of overall rates of reinforcement.

The changes in local rates of responding cannot be accounted for solely in terms of time since reinforcement. The distribution of responses throughout a given period of time since reinforcement can be manipulated within VI schedules by changing the distribution of intervals (*e.g.*, from an arithmetic to a geometric progression of intervals; Ferster and Skinner, 1957). A variable that may operate together with time since reinforcement, however, is probability of reinforcement or some derivative of this probability. If a responding organism reaches a time after reinforcement equal to the longest interval in a VI schedule, the probability that the next response will be reinforced is 1.0. If, however, the organism has not yet reached that time, the probability is less than 1.0, and depends on the number of intervals that end at or after the time that the organism has reached. In the present arithmetic VI schedules, therefore, probability of reinforcement increased as time passed since reinforcement.

The calculation of probability of reinforcement is considered in greater detail in Exp. 3, in which the probability of reinforcement was explicitly manipulated. It is sufficient to note here that both probability of reinforcement and local rates of responding increased as time elapsed since reinforcement. The overall-rate functions (Fig. 1) and the local-rate functions (Fig. 3) may therefore be similar because the changes in the overall rate of reinforcement provided by an interval schedule also changed the probability of reinforcement for responses within any fixed period of time. Thus, the overall- and the local-rate functions may depend on the same relationship between probability of reinforcement and subsequent responding.

Relationship between overall and local rates of responding. This relationship between local and overall rates of responding suggests that a given overall rate of responding may not be determined directly by an overall rate of reinforcement. Rather, a schedule may produce a given overall rate of responding through its effects on local rates of responding at different times after reinforcement. The way in which local rates of responding contribute to overall rates of responding must therefore be considered.

An overall rate of responding is a weighted average of the local rates of responding at successive times after reinforcement. The early times after reinforcement are weighted more heavily than the later times because the early times represent a larger proportion of the total time in the schedule. For example, within the first t sec after reinforcement in the arithmetic VI schedules, responding was possible 14 times as often as within the last t sec (first and last points on each function in Fig. 2 and 3; cf. Method). Thus, a consistent change in the local rate of responding early after reinforcement would produce a greater change in the overall rate of responding than the same consistent change late after reinforcement. An alternative measure, therefore, is the average of the successive local rates of responding maintained by a particular schedule (e.g., the average of all the points on a given function in Fig. 2), because this measure does not weight early local rates more heavily.

When local-rate functions are similar at different rates of reinforcement (as to a first approximation for Pigeons 118, 129, and 279 in

Fig. 3), the substitution of average local rate for overall rate of responding does not alter the functional relation between rate of responding and overall rate of reinforcement (Fig. 1); the average local rates and the overall rates of responding will differ slightly, by a multiplicative constant. This is not necessarily the case, however, when the local-rate functions are dissimilar. For example, in the 12.0-sec and 23.5-sec functions for Pigeon 121, the 23.5-sec function for Pigeon 278, and the 12.0-sec function for Pigeon 281 in Fig. 3, the local rates of responding shortly after reinforcement were relatively low compared to the local rates within other schedules for the same pigeons. The values of t in the 12.0-sec and 23.5-sec VI schedules were roughly 1.7 and 3.4 sec, respectively, and although rates of responding were high, occasional short pauses that occurred immediately after reinforcement reduced the number of responses in the early t -sec periods after reinforcement. Because these pauses were weighted more heavily in the overall rate of responding than in the average local rate, the overall rate was lower, relative to the average local rate, in these than in the remaining schedules. Inversely, the local rate of responding was relatively high after reinforcement for Pigeon 278 at VI 45.5-sec (Fig. 3), and the overall rate was higher, relative to the average local rate, in this than in the remaining schedules.

Figure 3 shows data from the initial determination of performance on each schedule. In three of the above cases (Pigeon 121 at VI 23.5-sec, Pigeon 281 at VI 12.0-sec, and Pigeon 278 at VI 45.5-sec), data from a redetermination were available. The redetermined local-rate functions (not shown in Fig. 3) deviated considerably less from other local-rate functions for the same pigeon than did the initial local-rate functions. These three cases represent three of the four largest discrepancies between initial and redetermined overall rates of responding (see Fig. 1), and it is of interest that the three discrepancies are each reduced by about 5 resp/min if initial and redetermined average local rates of responding are substituted for initial and redetermined overall rates of responding.

This observation is consistent with the assumption that the overall rate of responding is not directly determined by an overall rate of reinforcement. Reinforcement does not

produce a reserve of responses that are emitted irrespective of their distribution in time. Rather, a given rate of reinforcement produces a given overall rate of responding through its effects on local rates of responding at different times after reinforcement. The experiments that follow consider the effects of reinforcement on local rates of responding in detail, by varying the distribution of intervals in VI schedules.

EXPERIMENT 2: EFFECTS OF A ZERO-SEC INTERVAL IN AN ARITHMETIC VARIABLE- INTERVAL SCHEDULE

In the schedules of Exp. 1, the first response after a reinforcement was reinforced in one of every 15 intervals. This 0-sec interval may have had an effect on responding both immediately after reinforcement and later. The present experiment directly compared local rates of responding maintained by arithmetic VI schedules with and without a 0-sec interval. One consequence of the 0-sec interval was that the reinforced response was preceded by a latency (timed from the end of reinforcement) whereas the reinforced response in other intervals typically was preceded by an interresponse time (timed from the preceding response).

METHOD

Subjects and Apparatus

In sessions preceding Exp. 1, Pigeons 278 and 281 were exposed to two arithmetic VI schedules in the apparatus described previously. To permit a detailed examination of responding shortly after reinforcement, the recording circuitry cumulated responses separately during successive thirds of the first and second t sec of each interval.

Procedure

In the first schedule, t sec were added to each interreinforcement interval of the arithmetic VI schedule of Exp. 1. This increased the mean interval from 7 t to 8 t sec and eliminated the 0-sec interval; the shortest interval in the schedule was 1 t sec. The second schedule was the same as the schedule of Exp. 1; it included the 0-sec interval. With t equal to about 15.4 sec, the first schedule was arranged for 29 sessions (arithmetic VI 123-

sec with no 0-sec interval) and the second schedule for 21 sessions (arithmetic VI 108-sec with 0-sec interval).

RESULTS

Local rate of responding as a function of absolute time since reinforcement is shown in Fig. 5. The first six points on each function represent local rates during successive thirds of the first and second t sec after reinforcement. For Pigeon 278, rates of responding remained roughly constant after about 50 sec since reinforcement in both schedules, and for Pigeon 281, rates of responding gradually increased up to the longest time since reinforcement in both schedules (*cf.* Fig. 2 and 3).

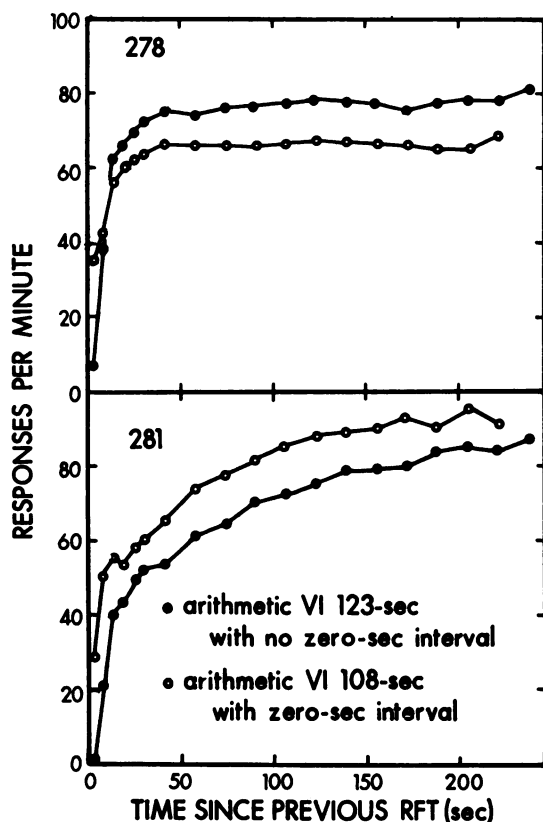


Fig. 5. Rate of key-pecking as a function of time since reinforcement in arithmetic VI schedules with and without a 0-sec interreinforcement interval.

The effect of the 0-sec interval was restricted primarily to the time shortly after reinforcement (first two or three points on each function). Relative to the schedule with no 0-sec interval, the 0-sec interval added a larger increment to the local rate of responding than would have been produced if only a single re-

sponse immediately after reinforcement was added to each interval. One additional response at the beginning of each interval would have raised the local rate of responding immediately after reinforcement by about 12 resp/min and would have had no effect on subsequent local rates of responding. The actual increment was of the order of 30 resp/min and persisted to some extent in subsequent local rates of responding (second and third points on each function).

The overall rates of responding maintained by the VI 123-sec and VI 108-sec schedules were 63.7 and 63.2 resp/min for Pigeon 278 and 61.1 and 73.7 resp/min for Pigeon 281. Thus, the overall rate of responding was higher for the schedule with no 0-sec interval for Pigeon 278 and lower for Pigeon 281. In Fig. 5, the difference is exaggerated for Pigeon 278 because the figure does not reflect the relatively large contribution of the high rate of responding shortly after reinforcement to the overall rate of responding maintained by the schedule with the 0-sec interval (Exp. 1, Discussion). The schedule with the 0-sec interval (VI 108-sec) provided about 5 rft/hr more than the schedule without the 0-sec interval (VI 123-sec), but the magnitude of the reversal for Pigeon 278 was well within the limits of variability suggested by the redeterminations in Fig. 1.

DISCUSSION

The increment in the local rate of responding immediately after reinforcement suggests that the 0-sec interval affected both the latency of the first response after reinforcement and the local rate of responding shortly after reinforcement. Continued exposure to the schedules with the 0-sec interval might have reduced the size of the increment, because first responses after reinforcement were occasionally reinforced whereas second and third were never reinforced. One factor that could have counteracted this effect was the occasional reinforcement of responses that followed the first response (about 15 sec later, at the end of the *t*-sec interval). Another possibility was that the reinforced first response in the 0-sec interval occasionally may have been preceded by a peck of insufficient force to operate the response key, with an effect on subsequent behavior equivalent to the reinforcement of a second peck after reinforcement.

Only pecks of sufficient force, however, produced a feedback click and the feedback presumably contributed to differentiation of the force of pecks over the course of the present experiment.

The fairly localized effect in time of the 0-sec interval suggests that it is reasonable to compare local rates of responding maintained at later times after reinforcement in VI schedules with different distributions of intervals even if some, but not all, of the schedules include a 0-sec interval. Such comparisons are made in Exp. 3, although the data presented here are limited. The data also suggest that reinforcement of the first response in each session, common to both schedules in Fig. 5, had at best a small effect on responding early in intervals compared to the effect of reinforcement of the first peck after a reinforcement in 0-sec intervals within the session.

EXPERIMENT 3: EFFECTS OF THE DISTRIBUTION OF INTERVALS IN VARIABLE-INTERVAL SCHEDULES ON CHANGES IN THE LOCAL RATE OF RESPONDING WITHIN INTERVALS

Experiment 1 demonstrated that local rate of responding increased as time passed since reinforcement in an arithmetic VI schedule. Evidence in the literature, however, demonstrates that VI schedules with other distributions of intervals have different effects. For example, Ferster and Skinner (1957) showed that local rates of responding decreased as time passed since reinforcement in a VI schedule in which the durations of intervals were derived from a geometric progression. Their demonstration that different distributions of intervals differently affect local rates of responding indicates that local rates are not controlled solely by time since reinforcement. The present experiment examined another variable: the probability of reinforcement at different times since reinforcement, which is determined by the distribution of intervals in a VI schedule.

The present treatment defines the probability of reinforcement as a relative frequency: the number of times the first peck is reinforced after a particular time since reinforcement divided by the number of opportunities for a peck after that time. This

statistic will be called reinforcements per opportunity (rft/op) by analogy to Anger's measure of response probability, interresponse times per opportunity (IRT/Op; Anger, 1956). The method of calculation is illustrated in Fig. 6, which diagrammatically shows an arbitrary schedule with intervals of 0, 20, 20, 60, 120, and 200 sec. The intervals are arranged in order of size, although they would be arranged in an irregular order in practice.

The first peck after a reinforcement is reinforced in the shortest interval but not in any of the remaining five intervals. The probability that this peck will be reinforced is therefore one-sixth (0.17). When the peck is reinforced, in the 0-sec interval, the reinforcement terminates the interval and serves as the starting point for another interval. When the peck is not reinforced, in the remaining five intervals, the probability of reinforcement for subsequent pecks becomes zero until the end of the next longer interval. In the example, the next opportunity for reinforcement occurs at 20 sec, when two of the five remaining intervals end. Thus, the first peck after 20 sec is reinforced on two of five opportunities, or with a probability of 0.40. Similarly, the first peck after 60 sec is reinforced with a probability of 0.33, the first peck after 120 sec with a probability of 0.50, and the first peck after 200 sec with a probability of 1.0. As Fig. 6 illustrates, the statistic can be calculated by dividing the number of intervals that end at a given time after reinforcement by the number that end at that time or later. (Reinforcements per opportunity is defined as the probability of reinforcement for the first response that occurs *after* a particular time since reinforcement. For convenience, the present discussion sometimes refers to the probability of reinforcement *at* a particular time.)

Reinforcements per opportunity rests on the assumption that, except at reinforcement, the organism cannot discriminate between a given time since reinforcement in one interval and the same time since reinforcement in an interval of different duration (*e.g.*, such discrimination could be based on the sequence of intervals). Another assumption is that the organism responds rapidly enough, when reinforcement becomes available at the end of one interval, to emit the reinforced response before the time at which the next longer interval ends. For example, the proba-

bilities of reinforcement for the first peck after reinforcement (in the 0-sec interval) and at 20 sec would not be separable if responses never occurred before 25 sec; the relevant probability of reinforcement would be 0.50 for both intervals. In most VI schedules, the rate of responding is high enough, relative to the time separating successive opportunities for reinforcement, to avoid violating this assumption (see, however, VI 12.0-sec and VI 23.5-sec in Exp. 1).

Probability of reinforcement does not necessarily increase monotonically as time passes since reinforcement. In Fig. 6, for example, the probability decreases from 0.40 at 20 sec to 0.33 at 60 sec, and then increases to 0.50 and 1.0 at later times after reinforcement. Each probability, however, occurs at a discrete point in time. The statistic is greater than zero only at times after reinforcement when intervals in the schedule end. An account of performance in terms of probability of reinforcement also must deal with other times, when the probability is zero. In addition, reinforcements per opportunity is independent of the absolute values on the time scale for an interval schedule. Probabilities would be unaffected, for example, if the values of the time scale of Fig. 6 were multiplied by 100. Because performance presumably would be different after this change, probability of reinforcement alone is probably not a sufficient determinant of performance; absolute durations must be taken into account by converting probabilities to local rates of reinforcement. Figure 6 illustrates a technique for computing such local rates. An opportunity for reinforcement is defined as a point on the continuum of time since reinforcement at which the probability of reinforcement is greater than zero, or at which at least one interval ends. The time over which a particular probability of reinforcement is assumed to be effective is arbitrarily taken as the time ranging from halfway back to the preceding reinforcement or opportunity for reinforcement and halfway forward to the next reinforcement or opportunity for reinforcement. This procedure takes into account the observation that a probability of reinforcement at a particular time since reinforcement can affect responding at both earlier and later times.

Consider, for example, the opportunity at

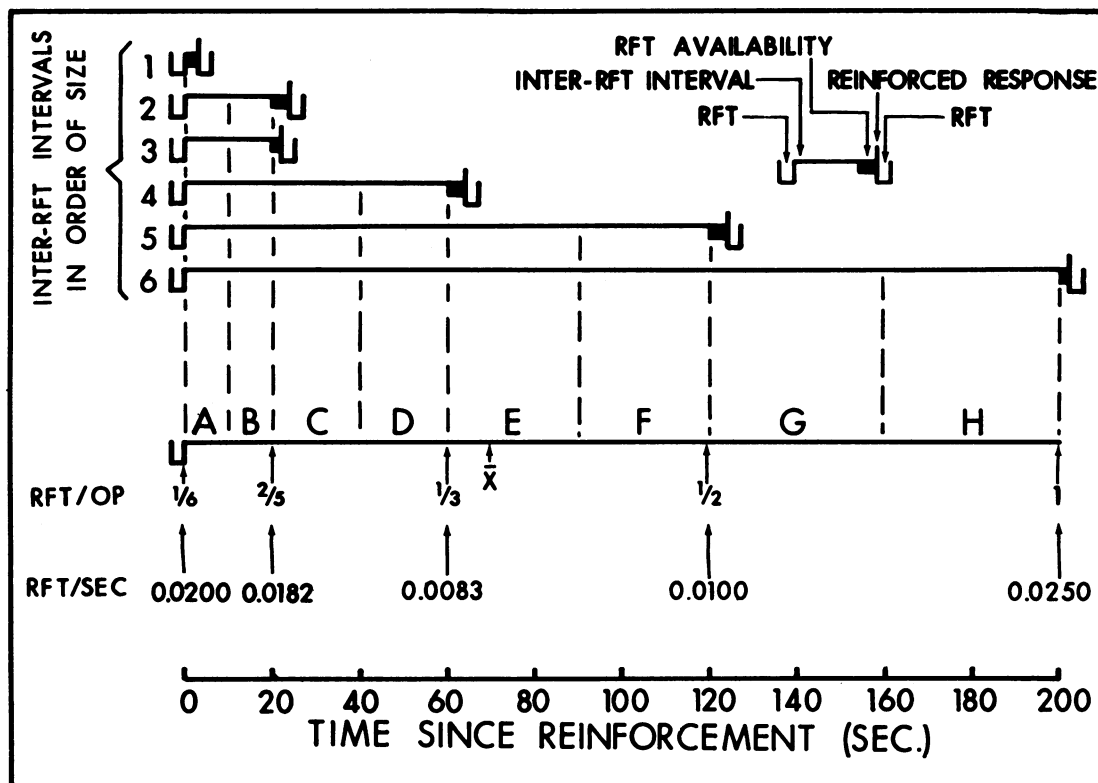


Fig. 6. Schematic presentation of a VI schedule illustrating the computation of two statistics discussed in the text. The upper part of the figure shows the six interreinforcement intervals of the schedule in order of size: 0-sec, 20-sec, 20-sec, 60-sec, 120-sec, 200-sec. Each interval is shown starting from a preceding reinforcement (rft). The first statistic, reinforcements per opportunity (rft/op), is a measure of probability of reinforcement: the number of occasions that reinforcement becomes available at a particular time since reinforcement divided by the number of occasions that the time since reinforcement is reached (e.g., reinforcement is available at 20 sec on two of five occasions). The second statistic, reinforcements per second (rft/sec), is a measure of local rate of reinforcement: the number of reinforcements within a particular period of time since reinforcement divided by the number of seconds spent in that period of time. The periods of time since reinforcement are arbitrarily taken as centered at a given opportunity for reinforcement and extending halfway back to the preceding reinforcement or opportunity for reinforcement and halfway forward to the next reinforcement or opportunity for reinforcement (e.g., for the two reinforcements at 20 sec, the periods of time marked B and C: five 10-sec periods and three 20-sec periods for a total of 110 sec).

60 sec in Fig. 6. The time over which this probability of reinforcement is considered effective is marked D and E (halfway back to the opportunity at 20 sec and halfway forward to the opportunity at 120 sec). The organism spends 120 sec within the period of time represented by D and E in each full sampling of the six intervals, and one reinforcement is arranged, at the end of the 60-sec interval. In other words, the rate of reinforcement within this period is one reinforcement per 120 sec (0.0083 rft/sec). Correspondingly, the local rate of reinforcement at 20 sec is given by the number of reinforcements arranged at 20 sec divided by the time

spent in periods B and C: this local rate is two reinforcements per 110 sec (0.0182 rft/sec). For the opportunity at 0 sec, which immediately follows a reinforcement, the local rate of reinforcement is based only on time period A. For the opportunity at 200 sec, after which a peck always terminates the interval with reinforcement, the local rate of reinforcement is based only on time period H.

With this calculation, the local rates of reinforcement at 0 and 200 sec after reinforcement are almost equal, whereas the probabilities of reinforcement at these times differ by a factor of six (0.166 and 1.0). Other plausible techniques for assigning time to successive op-

opportunities for the purpose of calculating local rates of reinforcement are possible, such as bisection of the time interval separating two successive opportunities using the geometric rather than the arithmetic mean, or the assignment to a given opportunity of the time since the last opportunity. The present technique, though arbitrary, seems to involve the simplest *ad hoc* assumptions.

To recapitulate, reinforcements per opportunity expresses a conditional probability: the probability that the pigeon's response will be reinforced, given that the pigeon has reached a certain time since the last reinforcement. Defined in this way, the statistic does not take into account the separation in time of different opportunities (ends of intervals). By taking into account the temporal separation of successive opportunities, probabilities of reinforcement can be converted into local rates of reinforcement.

The present experiments compared five VI schedules, each providing roughly the same overall rate of reinforcement (rft/hr) but with different distributions of intervals. One schedule was the arithmetic VI schedule of Exp. 1. Two of the other four schedules differed from the arithmetic VI schedule primarily by including extra short intervals. The extra short intervals produced a higher probability of reinforcement shortly after reinforcement than was produced at the same time after reinforcement in the arithmetic VI schedule. In another schedule, the distribution of intervals was such that the probability of reinforcement, given an opportunity for reinforcement, was roughly a linearly increasing function of the time since reinforcement. In the last schedule, the probability of reinforcement was held roughly constant over most of the range of time since reinforcement. The relationship between local rates of responding and the probabilities and local rates of reinforcement were examined within each schedule.

METHOD

Apparatus

The apparatus was as described in Exp. 1 and 2. The recording circuitry subdivided the first and second *t* sec of each interval so that responses were cumulated separately during successive thirds of these time periods. In ad-

dition, the constant-probability schedule, described in detail below, included interreinforcement intervals longer than those in other schedules. For this schedule, therefore, the last three counters grouped responses in the twelfth and thirteenth, the fourteenth and fifteenth, and the sixteenth and seventeenth *t* sec after reinforcement.

Subjects and Procedure

Four of the six pigeons of Exp. 1 were each assigned an average interreinforcement interval: for Pigeons 118 and 129, VI 108-sec (33.3 rft/hr); for Pigeon 278, VI 427-sec (8.4 rft/hr); and for Pigeon 279, VI 45.5-sec (79 rft/hr). The arithmetic VI schedule of Exp. 1 was then compared with the four other VI schedules, the component *t*-sec intervals of which are indicated in Table 2. The table lists the schedules in the order in which they were presented. Each session consisted of 61 reinforcements. The sessions of the arithmetic VI schedule were the last sessions of Exp. 1 except for Pigeon 279, for which 29 sessions of arithmetic VI 108-sec intervened between 15 sessions of arithmetic VI 45.5-sec and this pigeon's other schedules in the present experiment (*cf.* Table 1).

Schedules were changed only after the performance of each pigeon had been stable over a period of at least two weeks. Some schedules were continued for a large number of sessions so that long-term stability of the performances could be examined. Data from this experiment are averages over the last five sessions of each schedule.

In making up the distribution of interreinforcement intervals for the constant-probability VI schedule, it was not convenient to match the mean interval to that of the other VI schedules. Thus, the constant-probability schedule was VI 79-sec (45.5 rft/hr) for Pigeons 118 and 129, VI 379-sec (9.5 rft/hr) for Pigeon 278, and VI 40.5-sec (89 rft/hr) for Pigeon 279.

RESULTS

Two kinds of graphs summarize the VI schedules. Probability of reinforcement (rft/op) plotted as a function of time since reinforcement describes the schedule, and local rate of pecking plotted as a function of time since reinforcement describes the performance maintained by the schedule.

Table 2

Sequence of minimum interreinforcement intervals, mean interval, and number of sessions for five variable-interval schedules. Interreinforcement intervals are expressed in terms of the number of t-sec steps from one reinforcement to the next opportunity for reinforcement.

Schedule	Sequence of Intervals	Mean	Sessions
Arithmetic	14, 8, 11, 6, 5, 9, 2, 13, 7, 1, 12, 4, 10, 0, 3.	7	28*
Extra short interval, I	14, 8, 11, 6, 5, 9, 2, 12, 7, 1, 12, 4, 10, 1, 3.	7	109
"Linear"	13, 10, 10, 7, 4, 7, 7, 4, 10, 13, 1, 4, 10, 7, 10, 4, 7, 7, 10, 7, 7, 10, 4, 7, 10, 4, 1, 7, 4, 4.	7	37
Extra short interval, II	12, 1, 4, 13, 10, 1, 8, 11, 1, 14, 2, 1, 7, 14, 6.	7	95
Constant probability (rft/op = 0.1)	2, 10, 6, 17, 3, 5, 14, 3, 8, 15, 1, 13, 10, 9, 2, 3, 8, 2, 1, 2, 11, 5, 16, 9, 17, 6, 17, 7, 3, 4, 16, 1, 4, 17, 1, 7, 16, 12, 17, 8, 1, 4, 2, 16, 12, 13, 17, 3, 5, 7, 6, 11, 4, 1, 6, 14, 9, 16, 5, 15.	8.25	127

*For Pigeon 278, 26 sessions; for Pigeon 279, 15 sessions (see text).

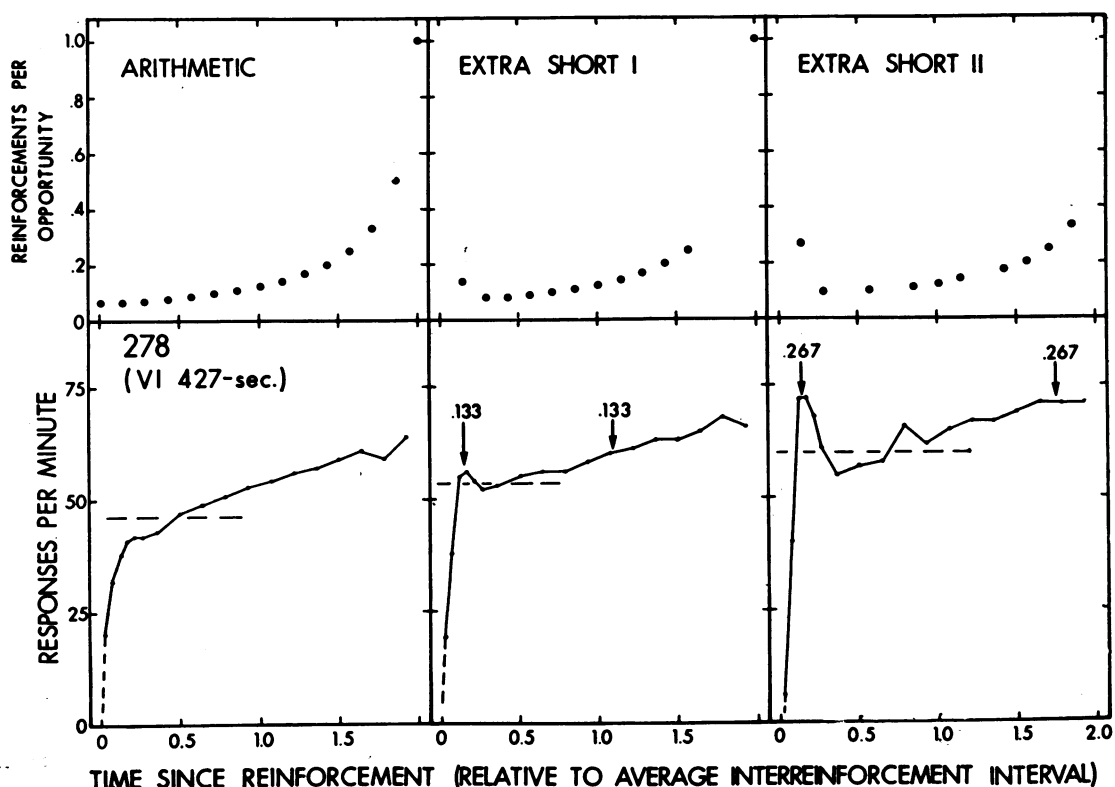


Fig. 7. Probability of reinforcement (upper frames) and the rate of Pigeon 278's key-pecking (lower frames) as a function of relative time since reinforcement in each of three VI schedules. The schedules differed in the number of short interreinforcement intervals and therefore in the probability of reinforcement (reinforcements per opportunity) shortly after reinforcement. Two different times after reinforcement at which probabilities of reinforcement were equal are indicated by arrows (extra short I and II). Dashed horizontal lines show the overall rates of key-pecking maintained by each schedule.

Extra-short-interval schedules. The arithmetic VI schedule and the two schedules with extra short intervals are described in the upper frames of Fig. 7. The arithmetic VI schedule arranged monotonically increasing probabilities of reinforcement (rft/op) at the ends of successive t -sec periods of time after reinforcement. The other two schedules (labeled extra short I and II) included extra t -sec intervals, and therefore provided a higher probability of reinforcement at t sec. In these schedules, the 0-sec interval was omitted (see Exp. 2) and the probabilities at later times also were changed from those in the arithmetic VI schedule, so that the three schedules had equal average values (see Table 2). The data supported the assumption that the changes later after reinforcement would have minor effects compared to those produced by the addition of more short intervals.

The lower frames in Fig. 7, for Pigeon 278, show that the arithmetic VI schedule maintained local rates of responding that increased as time passed since reinforcement (*cf.* Fig. 2), and that the two schedules with the extra short intervals maintained higher local rates of key-pecking at t sec after reinforcement than did the arithmetic VI schedule. A smaller increment was generated by the schedule with two intervals that ended at t sec after reinforcement (extra short I) than by the schedule with four intervals that ended at t sec (extra short II). Thus, the local rate of responding at t sec depended on the probability of reinforcement at that time. Some independence of the effect of probability of reinforcement from time since reinforcement is suggested by the rates of responding later after reinforcement when the probability of reinforcement was roughly the same as that at t sec (arrows; the later probabilities did not actually occur in the schedules but were interpolated from the adjacent non-zero probabilities).

Figure 8 shows the performances of the other three pigeons (118, 129, and 279) in the arithmetic and the extra-short-interval schedules. The local rates of pecking plotted against time since reinforcement are similar to those of Pigeon 278 in Fig. 7. The rate of pecking at t sec after reinforcement increased with the probability of reinforcement at t sec. The one exception was that only the second extra-short-interval schedule produced an increment

in the rate at t sec relative to that in the arithmetic VI schedule for Pigeon 129.

For all pigeons, the differences between the first points on each function can be attributed to the inclusion of a 0-sec interval in the arithmetic but not in the VI schedules with extra short intervals.

The overall rates of reinforcement were the same in each of the three schedules. The dashed horizontal lines in Fig. 7 and 8 show the overall rates of responding maintained by each schedule. The addition of extra short intervals produced increments in the overall rate of responding for Pigeon 278, but did not systematically affect overall rates of responding for the other three pigeons.

"Linear" schedule. The schedule in which probability of reinforcement was roughly linearly related to time since reinforcement ("linear" schedule) is compared with the arithmetic VI schedule in the upper frame of Fig. 9. In the "linear" schedule, non-zero probabilities of reinforcement occurred at only five discrete times after reinforcement, but the probabilities of reinforcement at successive opportunities increased more rapidly than in the arithmetic VI schedule.

The lower frame of Fig. 9 shows the performance of Pigeon 278. The local rate of responding increased as time passed since reinforcement in both the "linear" and the arithmetic VI schedules. Overall rate was higher in the "linear" than in the arithmetic VI schedule. The data for the other three pigeons are shown in Fig. 10. For Pigeons 129 and 279, the rate of key-pecking increased over time since reinforcement within both schedules, and for Pigeon 118, the rate of key-pecking decreased at later times after reinforcement in the "linear" schedule. For these three pigeons, overall rate was lower in the "linear" than in the arithmetic VI schedule.

The general similarity of the performances maintained by the arithmetic and "linear" schedules, given the considerable differences in the probabilities of reinforcement at particular times, appear inconsistent with the findings obtained with the schedules containing the extra short intervals. But the differences between these and arithmetic VI schedules were primarily in the probabilities of reinforcement shortly after reinforcement. These comparisons suggest, therefore, that the effect of a change in the probability of rein-

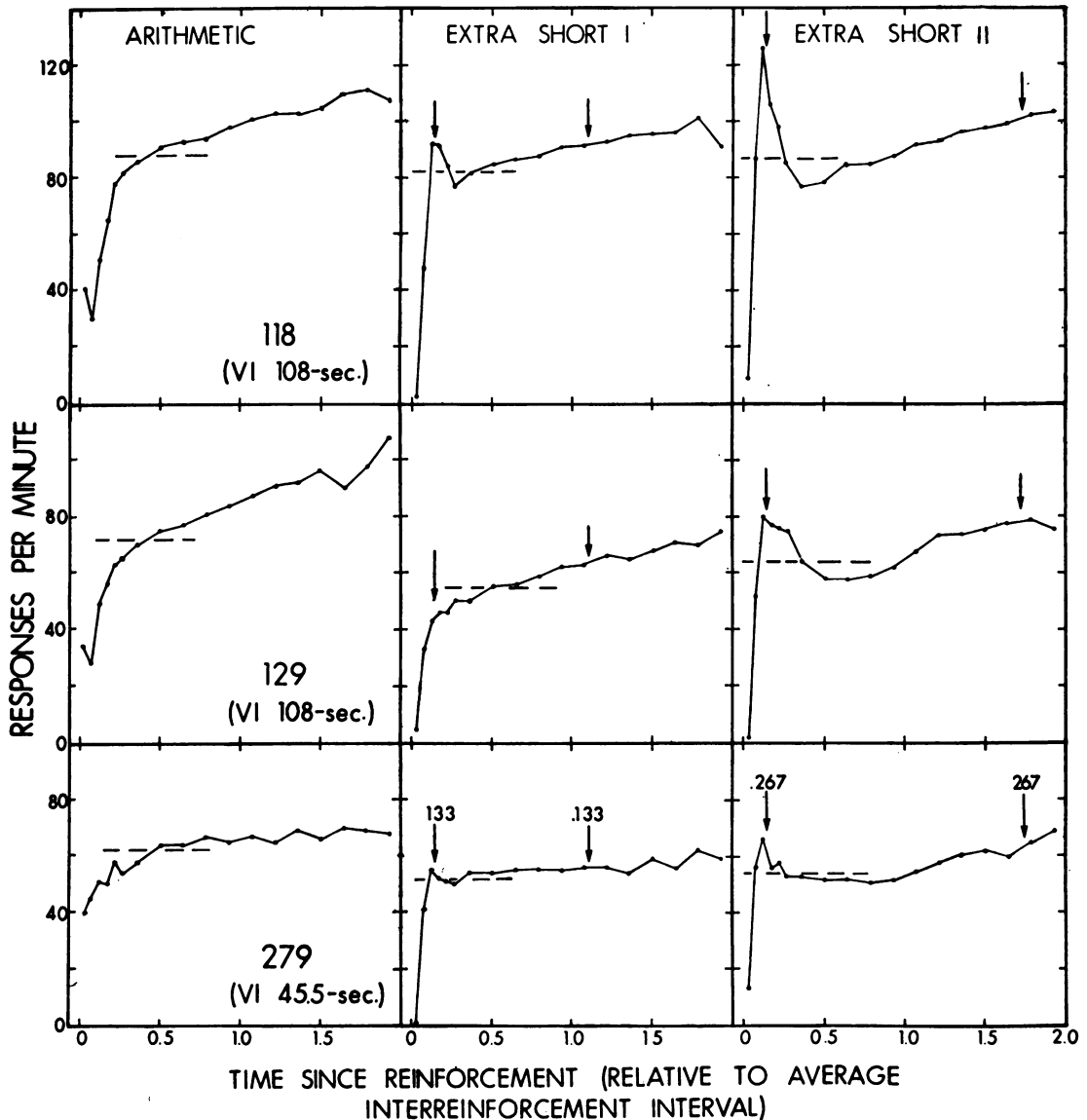


Fig. 8. Data from three VI schedules for three additional pigeons. Details as in Fig. 6.

forcement may depend on the time since reinforcement or on the separation of different probabilities of reinforcement along the continuum of time since the previous reinforcement.

Constant-probability schedule. The effects of a roughly constant probability of reinforcement over most of the range of time since reinforcement were examined in a schedule related to the random-interval schedules of Farmer (1963) and Millenson (1963), and to the constant-probability interval schedule arranged by Chorney (1960) according to the

specifications of Fleshler and Hoffman (1962), both of which are discussed in detail in Appendix II. In the present constant-probability VI schedule, shown in the upper frame of Fig. 11, the probability of reinforcement remained equal to 0.10 ± 0.02 over a range of time since reinforcement within which, in the arithmetic VI schedule, this probability increased almost five-fold, from 0.07 to 0.33. At the very late times since reinforcement, the probability of reinforcement necessarily increased, because the series had to contain a longest interval.

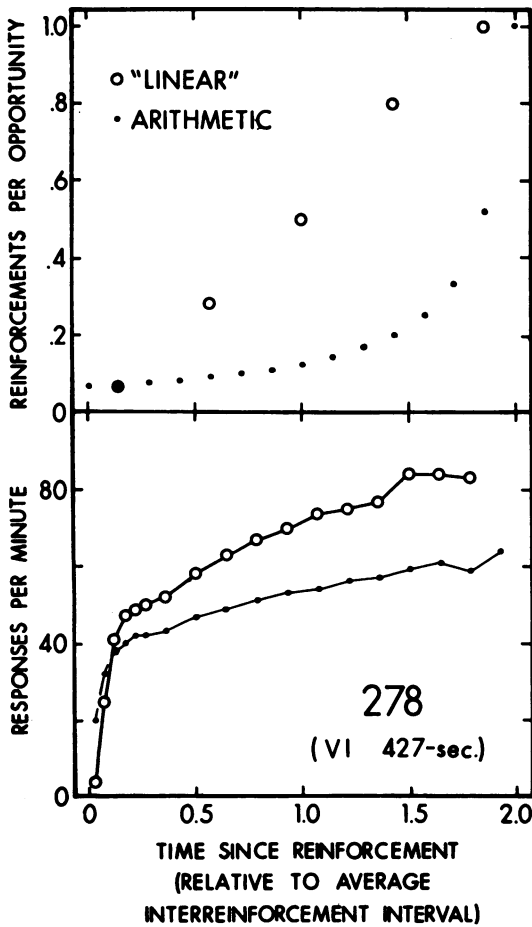


Fig. 9. Probability of reinforcement (reinforcements per opportunity) and rate of key-pecking as a function of time since reinforcement in a "linear" VI schedule. In this schedule, the probability of reinforcement, when not zero, was roughly proportional to time since reinforcement. The arithmetic VI schedule is presented for comparison.

The performance maintained by the constant probability and the arithmetic VI schedules are compared, for Pigeon 278, in the lower frame of Fig. 11. When the probability of reinforcement was held constant, the local rate of responding remained roughly constant throughout the interval between reinforcements. The increase in rate was only about 2 resp/min over the time from 2t to 17t sec, or roughly one-tenth the increase over the same range of time in the arithmetic VI schedule. A slight increase in response rate might have been expected, even in the constant-probability VI schedule, because the probability of reinforcement did increase eventually to 1.0 at the latest times after

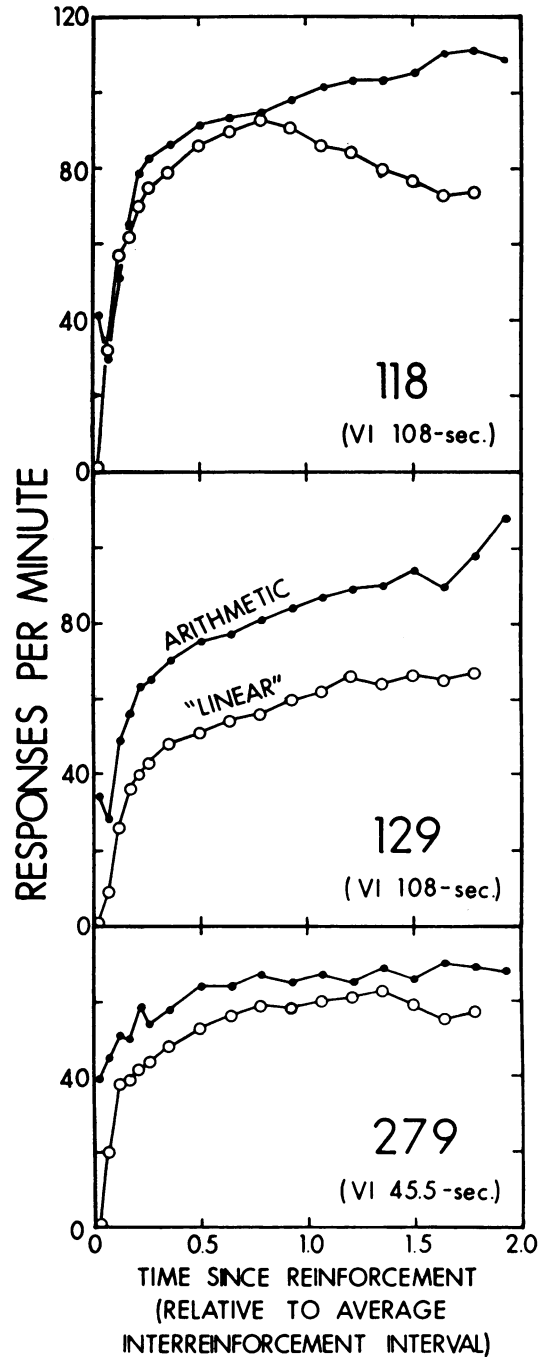


Fig. 10. Data from the "linear" VI schedule for three additional pigeons. Details as in Fig. 9.

reinforcement. Responding began at a low rate within intervals of the constant-probability schedule, probably because no 0-sec interval had been included in the schedule, but the rate increased rapidly during the first t and part of the second t sec.

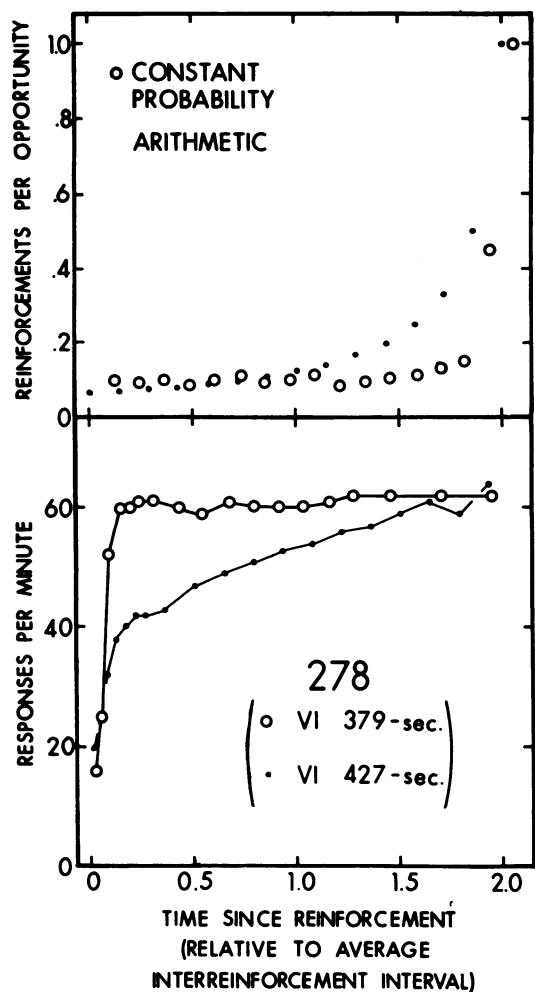


Fig. 11. Probability of reinforcement (reinforcements per opportunity) and rate of key-pecking as a function of time since reinforcement in a constant-probability VI schedule. In this schedule, the probability of reinforcement remained roughly constant until the latest times after reinforcement, when it increased abruptly to 1.0. The arithmetic VI schedule is presented for comparison.

The performances of the three other pigeons are shown in Fig. 12, again compared with the performances maintained by the arithmetic VI schedule. For all three pigeons, the local rate of responding changed considerably less over most of the range of time since reinforcement in the constant-probability schedule than it did in the arithmetic VI schedule. A transitory high local rate of responding shortly after reinforcement, for Pigeon 279 and to a lesser extent for Pigeon 118, may have persisted from the previous schedule with additional short intervals (Table 2). If so, it is not clear why

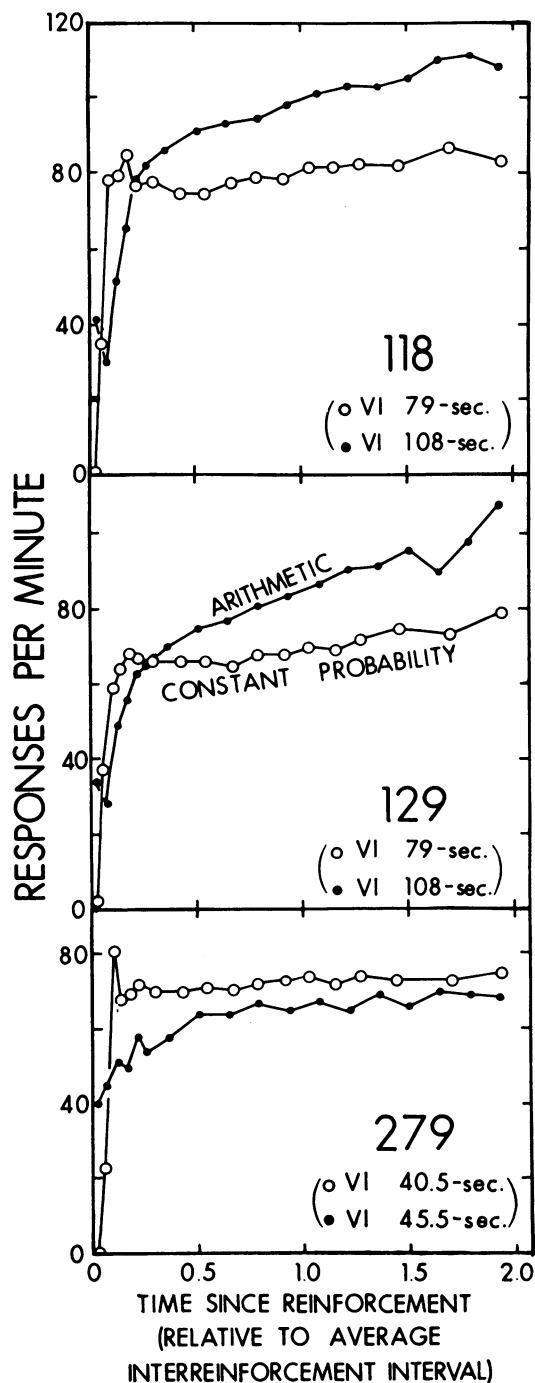


Fig. 12. Data from the constant-probability VI schedule for three additional pigeons. Details as in Fig. 11.

the peak did not similarly persist in the performances of the other birds. If the very early times after reinforcement have characteristics that affect the local rate of responding main-

tained by a given probability of reinforcement, it may be relevant that the absolute value of the constant-probability VI schedule, and therefore the duration of the short interval, was shortest for Pigeon 279.

Figure 13 shows a cumulative record of Pigeon 118's performance on constant-probability VI 79-sec, and may be compared with Fig. 4, a record of arithmetic VI 108-sec for the same pigeon. The record in Fig. 13 shows that the constant-probability VI schedule maintained a roughly constant rate of responding within each individual interval. Thus, the constancies in local rate shown in Fig. 11 and 12 were not artifacts of averaging performances over many intervals. Any consistent effects on responding within successive intervals that might have been caused by the particular sequence of intervals were not evident in the cumulative records. If such effects were present, they were small and will be disregarded here.

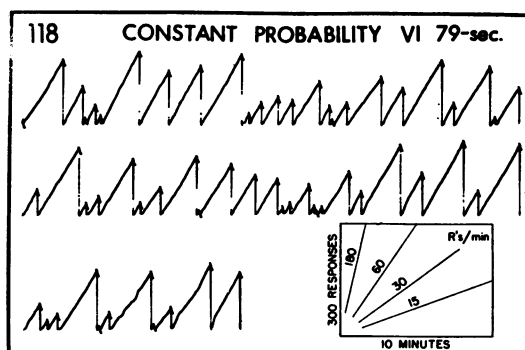


Fig. 13. Cumulative record of a full session of key-pecking maintained by a constant-probability VI schedule with a mean interreinforcement interval of 79 sec (Pigeon 118). The recording pen reset to baseline after each reinforcement, indicated by diagonal pips. Compare Fig. 4.

DISCUSSION

Distributions of intervals in variable-interval schedules. In the arithmetic and "linear" VI schedules, two schedules in which the probability of reinforcement increased as time passed since reinforcement, local rates of responding also increased as time passed. The increases in local rate were somewhat comparable in the two schedules despite considerable differences in the way the probability of reinforcement changed over time (Fig. 9 and 10). When the probability of reinforcement early after reinforcement was made high relative to

the probability at the same time in the arithmetic VI schedule, by the addition of extra short intervals, the local rate of responding at that time became relatively high (Fig. 7 and 8). Finally, when the probability of reinforcement was held roughly constant over most of the range of time since reinforcement, in the constant-probability VI schedule, local rates of responding remained relatively constant as time passed since reinforcement (Fig. 11 and 12).

Cumulative records presented by Ferster and Skinner (1957, Ch. 6) from schedules roughly equivalent to the arithmetic and the extra-short-interval VI schedules support the present findings: local rates of responding increased as time passed since reinforcement in the former schedules, and were relatively high shortly after reinforcement in the latter schedules. Ferster and Skinner also studied two other schedules, the geometric and the Fibonacci, which supplement the present schedules.

A geometric VI schedule consists of a sequence of intervals in which the duration of a given interval is equal to the duration of the next shorter interval multiplied by a constant (by this specification, Ferster and Skinner's schedules are only approximately geometric). With a constant of 2, for example, one such schedule consists of the following intervals in an irregular order: 1, 2, 4, 8, 16, etc. sec. A Fibonacci VI schedule consists of a sequence of intervals in which the duration of a given interval is equal to the sum of the durations of the next two shorter intervals, as, for example, in an irregular ordering of the following intervals: 1, 1, 2, 3, 5, 8, 13, etc. sec.

In both of these schedules, the probability of reinforcement increases monotonically to 1.0 over successive opportunities for reinforcement (except for the first opportunity after reinforcement in the Fibonacci schedule, because the shortest interval is represented twice in that sequence of intervals). For both of these schedules, Ferster and Skinner's cumulative records show that local rates of responding decreased as time passed since reinforcement. This demonstration, that local rates of responding may decrease even while probabilities of reinforcement increase, indicates again that something more than probability of reinforcement alone must be taken into account in the analysis of performance within intervals of VI schedules.

Further evidence is provided in Fig. 14, which shows data obtained by Chorney (1960) with arithmetic, geometric, and constant-probability VI 3-min schedules. The upper frames describe the schedules in terms of reinforcements per opportunity; the lower frames present local rates of responding averaged across data from three pigeons for each schedule. Each pigeon was exposed to only one schedule for about 26 sessions of 60 to 80 reinforcements each. Chorney's arithmetic and geometric VI schedules correspond to the examples of these two schedules already discussed: successively longer intervals differed in the arithmetic schedule by an additive constant, and in the geometric schedule by a multiplicative constant.

The constant-probability VI schedule, based on a formula proposed by Fleshler and Hoffman (1962), differed in its derivation from the constant-probability schedule of the present experiments. If a random generator arranged a constant probability of reinforcement within successive equal periods of time since reinforcement, the frequencies of different inter-reinforcement intervals would decline exponentially as a function of interval duration. In effect, Fleshler and Hoffman took this theoretical frequency distribution of intervals and divided it into equal areas, or, in other words, into successive class intervals in each of which an equal number of intervals ended. These class intervals became larger the longer the time since reinforcement because of the exponentially decreasing form of the frequency distribution. The average intervals of each of these class intervals were then taken as the constituent intervals of Fleshler and Hoffman's constant-probability schedule. One effect of this procedure was that the probability of reinforcement taken over extended periods of time since reinforcement was held roughly constant. For example, in the constant-probability VI schedule arranged by Chorney, 14 of the 25 intervals ended within the first 150 sec after reinforcement, or with a probability of 0.56; six of the remaining 11 intervals ended within the next 150 sec after reinforcement, or with a probability of 0.55; and in the next two 150-sec periods, the probabilities were 0.60 and 0.50, respectively (after 600 sec, when only the longest interval remained, the probability was necessarily 1.0).

The difference between two kinds of constant-probability VI schedules may be summarized as follows: the Fleshler and Hoffman schedule varied the separation of successive opportunities for reinforcement in time while holding equal the relative frequencies of the intervals ending at each opportunity; the present schedule spaced successive opportunities for reinforcement uniformly in time while varying the relative frequencies of the intervals ending at each opportunity. Some of the implications of those two methods of arranging constant-probability VI schedules are discussed in Appendix II.

Each of the schedules arranged by Chorney consisted of 25 intervals. In the arithmetic schedule, the intervals ranged from 1.0 to 358.6 sec with an additive constant of 14.9 sec. In the geometric schedule, the intervals ranged from 1.0 to 1150.0 sec with a multiplicative constant of 1.341. In the constant-probability schedule, the intervals ranged from 3.6 to 714.0 sec. The different ranges, produced when the mean value of each schedule was set at 180 sec, are reflected by the different scales for the abscissas of Fig. 14. In each schedule, the same probabilities of reinforcement were represented at successive opportunities: from 0.04 (1/25) at the end of the shortest interval, to 1.0 at the end of the longest interval. The schedules differed only in the spacing of successive opportunities for reinforcement in time. In the arithmetic schedule, the time from one opportunity to the next was constant; in the geometric and constant-probability schedules, the time from one opportunity to the next increased as time passed since reinforcement, but later after reinforcement the increase was more rapid in the geometric than in the constant-probability schedule.

The data, which show the effects of the different temporal spacings of successive opportunities, consisted of average rates of responding in successive thirds of intervals of comparable duration, about 350 sec, in each schedule (unfilled circles), and average rates of responding in all those intervals greater than 100 sec in each schedule (filled circles). The former showed that, during the first 300 sec after reinforcement, local rates of responding increased slightly in the arithmetic schedule and decreased in both the geometric and constant-probability schedules. The latter

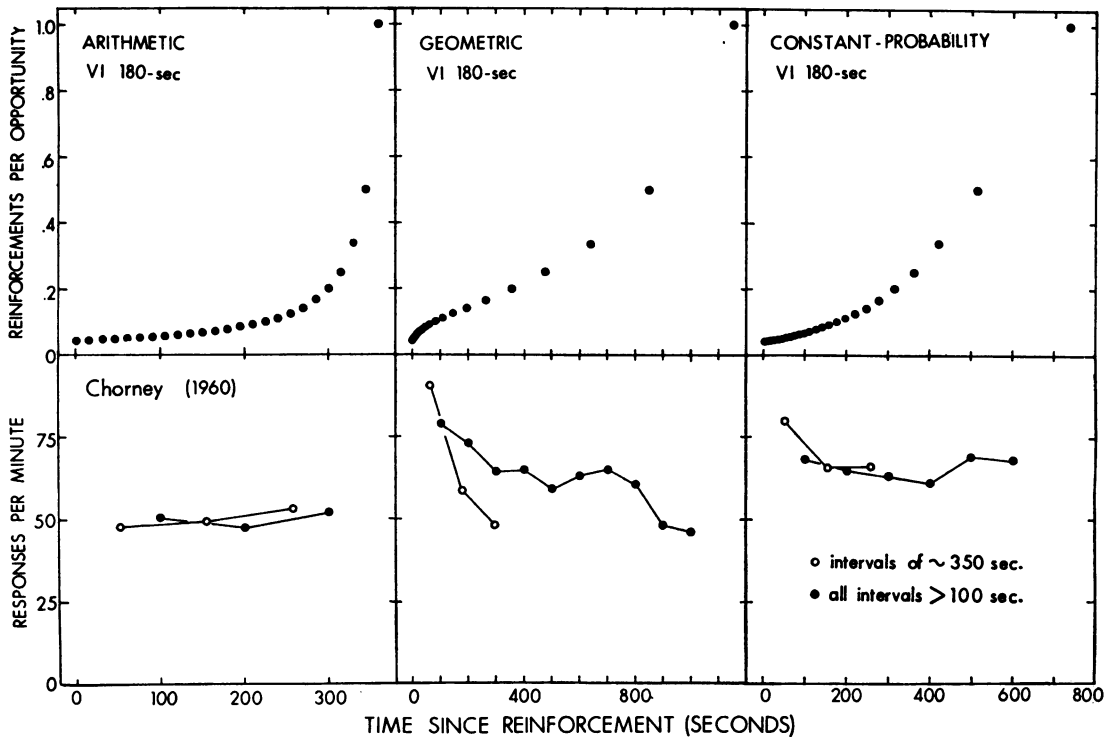


Fig. 14. Probability of reinforcement (reinforcements per opportunity) and the rate of key-pecking as a function of absolute time since reinforcement in three schedules, from Chorney (1960). Note the different abscissa scales. Details in text.

showed that the local rate of responding decreased markedly as time passed since reinforcement in the geometric schedule, but did not change systematically in the arithmetic and constant-probability schedules. In summary, in the arithmetic schedule, the evidence for an increase in local rate of responding as time passed since reinforcement was ambiguous; in the geometric schedule, local rate decreased as time passed since reinforcement; and in the constant-probability schedule, local rate was fairly constant over most of the range of time since reinforcement, but was relatively high shortly after reinforcement. Taking into account the relatively short experimental histories on which these data are based, they are in reasonable agreement with the present findings and with other findings in the literature.

Local rates of reinforcement. The differences in performance produced by a fixed sequence of probabilities of reinforcement, when the temporal separations of successive opportunities for reinforcement were varied, indicate that the present analysis must be extended from probabilities of reinforcement to local

rates of reinforcement. The basic premise in converting probabilities of reinforcement to local rates of reinforcement is that the effect of a given probability of reinforcement may spread over time and may depend on the closeness in time of other opportunities for reinforcement. A probability of reinforcement of 1.0 at one time, for example, may maintain responding at earlier times and may not maintain as high a rate when it is separated from the preceding opportunity by a long time (e.g., 300 sec in the geometric VI schedule of Fig. 14) as when it is separated from the preceding opportunity by a short time (e.g., 15 sec in the arithmetic VI schedule of Fig. 14). Local rates of reinforcement, illustrated in Fig. 6, take the separation of successive opportunities for reinforcement into account; they are calculated by dividing the number of reinforcements at a given opportunity by the period of time within which that opportunity is isolated. Local rates of reinforcement also can be considered equivalent to probabilities of reinforcement averaged over extended periods of time.

Local rates of reinforcement within the five VI schedules of the present experiment and in a geometric VI schedule (intervals of 10, 20, 40, 80, and 160 sec) are shown in Table 3. The mean values of the schedules were chosen so that each schedule could be represented in terms of intervals that were integral multiples of 10 sec. Local rates of reinforcement are shown only at opportunities for reinforcement (times at which at least one interval in the schedule ended); the local rates take into account the absence of opportunities for reinforcement at times for which there are no entries in Table 3. The opportunity at 0 sec in the arithmetic VI schedule is omitted from the table for reasons to be discussed below.

Table 3 shows that the local rate of reinforcement increased with time since reinforcement in both the arithmetic and "linear" VI schedules. Except for the opportunity at 10 sec after reinforcement, it also increased in the VI schedules with the extra short intervals. In the constant-probability VI schedule, the local rate of reinforcement remained relatively constant, except at the latest times after reinforcement when the probability of reinforcement necessarily increased to 1.0. In the geometric VI schedule, the local rate of reinforcement decreased as time passed since reinforcement, except at the terminal opportunity (160 sec).

The conversion of these local rates of reinforcement to those for equivalent VI schedules with different mean intervals involves only the multiplication of each of the local rates by a constant. For an arithmetic VI schedule with a mean of 35 sec, for example, in which each of the intervals in the first column of Table 3 is halved, the local rates of reinforcement in the table are multiplied by two.

Corresponding changes in local rates of reinforcement over time since reinforcement occur in the schedules arranged by Chorney. Except for some deviations at the earliest and latest opportunities for reinforcement, local rate of reinforcement increased monotonically as time passed since reinforcement in the arithmetic VI schedule, decreased monotonically in the geometric VI schedule, and remained roughly constant in the constant-probability VI schedule. In other words, these directions of change in local rate of reinforcement are characteristic, respectively, of these three classes of distributions of intervals in VI schedules, and changes in local rate of reinforcement correspond in direction to the changes in local rate of responding observed in a given schedule (an increasing local rate of responding in the arithmetic VI schedule, a relatively high local rate of responding shortly after reinforcement in the extra-short-interval VI schedules, and so on). Never-

Table 3

Local rates of reinforcement (rft/hr) at successive opportunities for reinforcement in six variable-interval schedules. Details in text.

Time Since rft (sec)	Arithmetic VI 70-sec*	Extra Short I VI 70-sec	Extra Short II VI 70-sec	"Linear" VI 70-sec	Constant- Probability VI 82.5-sec	Geometric VI 62-sec
10	27	51	111	13	38	80
20	29	29	23		35	72
30	31	31			37	
40	34	34	19	40	34	51
50	38	38			38	
60	42	42	28		42	
70	48	48	48	80	36	
80	55	55	41		39	45
90	66	66			44	
100	79	79	42	160	33	
110	103	103	80		36	
120	144	288	103		40	
130	240		144	240	45	
140	720	360	720		51	
150					60	
160					209	90
170					720	

*Local rate of 55 rft/hr at 0 sec is omitted (see text).

theless, changes in the local rate of reinforcement are large compared to the changes in the local rate of responding. The local rate of reinforcement in the arithmetic VI schedule, for example, increases by a factor of almost 40 over the time from 10 to 140 sec after reinforcement, whereas the local rate of responding increases by a much smaller factor. In Exp. 1, however, the functions relating overall rate of responding to overall rate of reinforcement were generally monotonically increasing but negatively accelerated; beyond about 50 rft/hr, large changes in the overall rate of reinforcement produced relatively small changes in the overall rate of responding. It is therefore appropriate to compare the local rates of responding maintained by different local rates of reinforcement (Fig. 7-10) with the overall rates of responding maintained by different overall rates of reinforcement (Fig. 1; see also the top graph of Fig. 28, Appendix I).

Figure 15 compares for each pigeon the local rates of responding maintained by the arithmetic, extra-short-interval, and "linear" VI schedules (obtained: connected filled circles) and, from Fig. 1, the overall rates of responding maintained by overall rates of reinforcement that corresponded to the local rates of reinforcement at successive opportunities within each schedule (calculated: unconnected unfilled circles). The correspondence between the two sets of data is by no means perfect, but several features are encouraging. The two sets of data tend to increase and decrease together, even when they differ considerably in absolute value. In several cases, both sets of data agree fairly well in absolute rate as well as in the direction of change over time since reinforcement. Finally, some of the idiosyncratic characteristics of the performances of different pigeons, as in the larger rate changes for Pigeon 118 than for Pigeon 279, are reflected in both sets of data.

The disagreements between the two sets of data stem from several sources. One of the most important is the adequacy of the overall-rate data from Fig. 1. The data in Fig. 1 show average rates maintained by different overall rates of reinforcement, but the range of variation at a given overall rate of reinforcement is indicated only by the extent to which redeterminations differed from original determinations. Redetermined overall rates of responding were generally higher than the

original rates. It therefore may be important that the local rates of responding in the schedules in Fig. 15 were generally higher, for three of the four pigeons, than the overall rates derived from Fig. 1, because the schedules in Fig. 15 were presented later than those in Fig. 1.

In addition, most of the overall rates of responding plotted in Fig. 15 were obtained indirectly, by interpolation between actual data points in Fig. 1, or, in the case of Pigeon 278 at VI 427-sec, by the linear extrapolation to zero from the lowest rate of reinforcement (8.4 rft/hr). For example, most of the local rates of reinforcement within the VI 427-sec schedules were lower than any of the overall rates of reinforcement arranged for this pigeon in Exp. 1, and this extrapolation yielded most of the overall rates of responding that were considerably lower than the local rates within each schedule for this pigeon in Fig. 15. Furthermore, the overall rates of responding in Fig. 1 were obtained with arithmetic VI schedules, in which local rates varied with time since reinforcement, rather than with constant-probability VI schedules. As indicated in Exp. 1 (Discussion), this characteristic of arithmetic VI schedules may have affected the overall-rate functions.

Variability in the performances maintained by the schedules in Fig. 15 also contributed to the disagreement between the two sets of data. The two most obvious cases are the idiosyncratic performance of Pigeon 118 in the "linear" schedule, within which the local rate of responding decreased at later times since reinforcement, and of Pigeon 129 in the first extra-short-interval schedule, within which the local rate of responding remained low shortly after reinforcement.

Finally, some systematic disagreement is evident at the earliest and the latest times since reinforcement. In the arithmetic schedule, the two sets of data disagree most at short times after reinforcement for Pigeons 118 and 279, and would do so also for Pigeons 129 and 278 if the two sets of data were adjusted to eliminate the differences in absolute value. In the extra-short-interval schedules, the overall rate of responding plotted at the latest time since reinforcement is relatively high in both schedules for Pigeon 118, in the first schedule for Pigeon 278, and in the second schedule for Pigeon 129. These

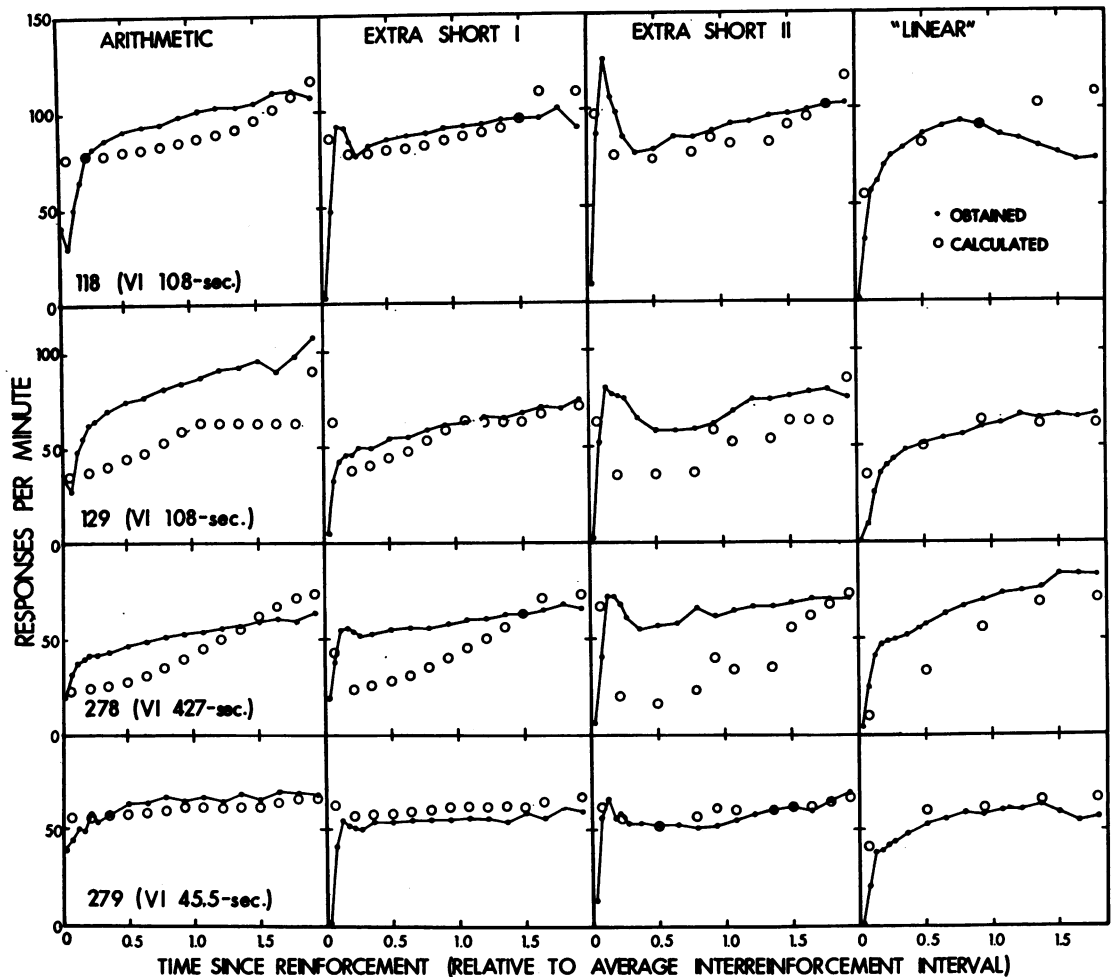


Fig. 15. Comparison of local rates of responding obtained in four VI schedules (Fig. 7-10) and local rates of responding calculated from overall rates of responding (Fig. 1) and local rates of reinforcement (Fig. 6 and Table 3). Details in text.

differences probably depend on the calculation of local rates of reinforcement (Fig. 6) rather than on the properties of the performances and their controlling variables. There is no reason to believe that the arbitrary method of calculation of local rates of reinforcement takes into account either the properties of the 0-sec interval (Exp. 2), which was arranged in the arithmetic but not the other schedules of Fig. 15, or of the latest time after reinforcement, at which the probability of reinforcement necessarily increases to 1.0 and at which the calculation of the local rate of reinforcement is unique in that it is based on periods of time preceding but not following the opportunity for reinforcement.

Adjustments could be made in the method of calculating local rates of reinforcement that would reduce the disagreements in the two sets of data at the earliest and latest times since reinforcement (*cf.* discussion of Fig. 6). In view of the sources of disagreement, however, and in the absence of additional data, such adjustments seem premature. It is sufficient to note that, given the qualifications outlined, the agreement between the two sets of data is good enough to suggest that both the overall rate of responding maintained by different interval schedules and the local rates of responding as time passes within a particular interval schedule are controlled, at least in part, by the same

variable: rate of reinforcement. Because overall rates of reinforcement and overall rates of responding are simply weighted averages of the local rates, it also follows that the overall rate of responding is indirectly determined by the effects of different local rates of reinforcement as time passes, rather than directly determined by the overall rate of reinforcement.

Some additional evidence, supplementing that in Fig. 15, is relevant to the relationship between overall and local rates of responding. In Exp. 1 (Discussion), it was suggested that, except for some of the arithmetic VI schedules with shorter mean values, the local rate of responding for a particular pigeon changed in roughly the same way as time passed since reinforcement in most of the schedules studied (Fig. 3). This was approximately so for most schedules and most pigeons, but it is possible, furthermore, to account for some of the deviations by comparing the overall-rate functions (Fig. 1) and the local rates of reinforcement within different arithmetic VI schedules.

Compare, for example, Pigeon 278's performance in the arithmetic VI 108-sec and VI 427-sec schedules (Fig. 3, but more easily seen by comparing Fig. 5 and 7). The local rate of responding became fairly constant after about 50 sec in the VI 108-sec schedule whereas it increased over almost the entire range of time since reinforcement in the VI 427-sec schedule. The local rates of reinforcement ranged from 17.4 to 465 rft/hr in the former schedule and from 4.4 to 118 rft/hr in the latter schedule (1t to 14t sec, with t equal to 15.4 and 61.0 sec in the two schedules, respectively). Looking at the difference between the two schedules in another way, note that the local rate of reinforcement reached 25 rft/hr at about 5t sec in the VI 108-sec schedule and at about 12t sec in the VI 427-sec schedule. The two schedules therefore covered different parts of the overall-rate function shown for Pigeon 278 in Fig. 1. This function was fairly flat beyond about 25 rft/hr or over most of the range of rates of reinforcement locally represented in the VI 108-sec schedule, but it increased steeply up to about 25 rft/hr or over most of the range of rates of reinforcement locally represented in the VI 427-sec schedule.

In some other cases in which local rates of responding changed differently in different

arithmetic VI schedules for a particular pigeon (Fig. 3), the differences can be similarly related to the form of the overall-rate function for that pigeon. The major deviations for the arithmetic VI schedules with short mean values (*e.g.*, Pigeon 121 at VI 12.0-sec, Fig. 3) cannot be assessed in this way, for the reasons outlined in Exp. 1 and because the local rates of reinforcement at later times after reinforcement in those schedules exceeded the overall rates of reinforcement in Fig. 1 (in the arithmetic VI 12.0-sec schedule, for example, the local rate of reinforcement exceeded 300 rft/hr by 8t sec after reinforcement).

EXPERIMENT 4: OVERALL AND LOCAL RATES OF RESPONDING WITHIN THREE FIXED-INTERVAL SCHEDULES

The fixed-interval (FI) schedule is the limiting case of the VI schedule: the distribution of intervals is narrowed down to a single value. The performance maintained by an FI schedule is usually characterized by a pause before the first response in an interval, and then by a gradually increasing rate of responding as the end of the interval approaches. Occasionally, the rate passes through a maximal value some time before the end of the interval (Ferster and Skinner, 1957) or, after extended exposure to a fixed-interval schedule, the responding after the initial pause may be maintained at a relatively constant rate throughout the remainder of the interval (Cumming and Schoenfeld, 1958).

The present analysis cannot easily be applied to the FI schedule, which includes a single opportunity at which the probability of reinforcement is 1.0. This single opportunity combines two difficulties in the analysis: that of the earliest opportunity (end of the shortest interval), which is preceded by a reinforcement rather than by another opportunity, and that of the latest opportunity (end of the longest interval), at which the probability of reinforcement necessarily increases to 1.0. The present experiment therefore examined some properties of responding within fixed intervals. Three FI schedules were studied: FI 30-sec, FI 50-sec, and FI 200-sec.

METHOD

Apparatus

The standard experimental chamber was similar to that described in the preceding experiments. The response key was illuminated by an orange 6-w bulb. Reinforcement duration was 3 sec. The controlling and recording apparatus was located in a separate room, and included a stepping switch that arranged the FI schedules and distributed responses to 10 counters representing successive tenths of the interval.

Subjects and Procedure

Four adult, male, White Carneaux pigeons, maintained at about 80% of free-feeding body weight, were exposed to FI 50-sec, FI 200-sec, and FI 30-sec schedules in that order. Sessions of a different procedure (temporal discrimination: Reynolds and Catania, 1962) preceded FI 50-sec and intervened between FI 200-sec and FI 30-sec. Each FI schedule was maintained for approximately two months of daily sessions, at which time the performance of each pigeon had appeared stable (visual inspection of the data) for at least two weeks. Sessions of FI 50-sec and FI 30-sec consisted of 61 reinforcements: reinforcement of the first response of the session followed by reinforcement at the end of 60 intervals. Sessions of FI 200-sec consisted of only 31 reinforcements (30 intervals). Each interval was timed from the end of the preceding reinforcement. Data presented are averages over the last five sessions of each FI schedule.

RESULTS

Figure 16 shows local rates of responding in successive tenths of the fixed interval as a function of both absolute (left column) and relative (right column) time since reinforcement. In absolute time, the rate of responding increased most rapidly in the shortest fixed interval (FI 30-sec). In both the FI 30-sec and the FI 50-sec schedules, local rates of responding increased monotonically as time passed since reinforcement. In the FI 200-sec schedule, the local rate of responding began to decrease slightly about halfway through the interval for Pigeon 68, and decreased slightly shortly before reinforcement for Pigeon 236. About halfway through the 200-sec interval, the local rate of responding become

roughly constant for Pigeon 237. Local rate of responding as a function of absolute time since reinforcement was typically lower in FI than in arithmetic VI schedules, but the two sets of data have some similar characteristics (cf. Fig. 2, VI 12.0-sec, VI 23.5-sec, and VI 108-sec).

Replotting the data against relative time since reinforcement (right column) shows that, for all four pigeons, the FI 200-sec schedule maintained a relatively higher rate of responding early after reinforcement and a relatively lower rate of responding later after reinforcement than the other two schedules. This change in the pattern of responding in relative time contrasts with that observed in VI schedules (Fig. 3). Despite the duration for which the schedules were continued, the relatively high rate of responding maintained early after reinforcement in the FI 200-sec schedule may have persisted from reinforcement at an earlier time in the preceding FI 50-sec schedule. It is also possible that reinforcement of the first response in each session had effects similar to those of a 0-sec interval, but this interpretation is contradicted by the results of Exp. 2 and it is unlikely that such effects would be most marked in FI 200-sec.

Overall FI rates of responding are plotted against reinforcements per hour in Fig. 17 (left). No systematic relationship is evident. In general, however, the terminal rate of responding (the local rate of responding just before reinforcement) increased as the overall rate of reinforcement increased (right). These data differ considerably from those obtained with VI schedules (Fig. 1), in which both overall and local rates of responding increased with increases in the overall rate of reinforcement over a roughly comparable range.

DISCUSSION

The FI schedules demonstrate the extensive effects of reinforcement at one time after reinforcement on local rates of responding at other times. For example, reinforcement at 200-sec after reinforcement for Pigeon 68 maintained a considerable rate of responding over most of the range of time since reinforcement. Thus, the calculation of local rates of reinforcement, in the introduction of Exp. 3 (Fig. 6), probably underestimates the effect of reinforcement on local rates of responding at remote points in time. The calculation of

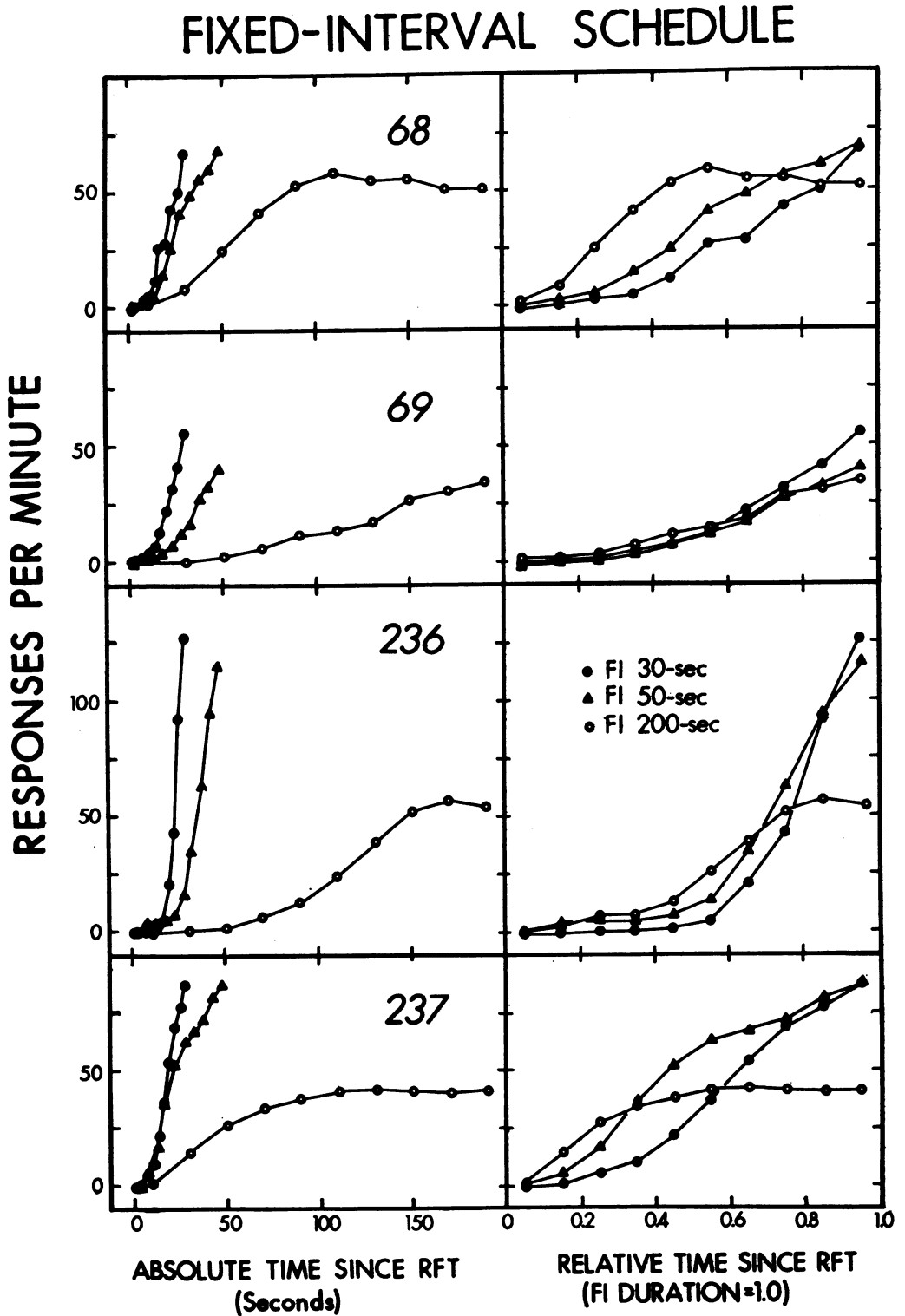


Fig. 16. Local rates of key-pecking maintained by three FI schedules as a function of absolute and relative times since reinforcement (four pigeons).

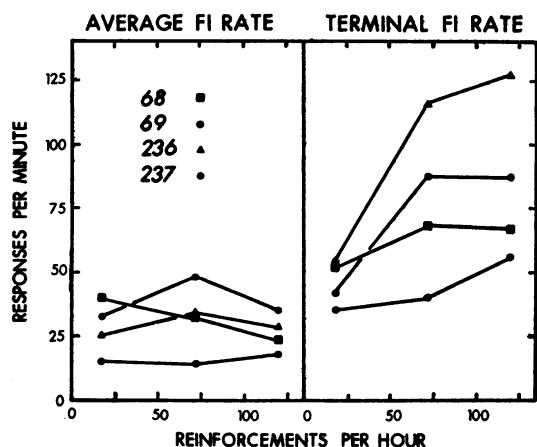


Fig. 17. Overall and terminal rates of key-pecking as a function of the rates of reinforcement provided by three FI schedules (four pigeons).

the local rate of reinforcement was based on a time extending only halfway back to a previous reinforcement or opportunity for reinforcement and halfway forward to the next reinforcement or opportunity for reinforcement. In many of the VI schedules discussed, this calculation involved a time of the order of only a few seconds, whereas reinforcement at one point in time affected rates of responding over a period of the order of 2 or 3 min in the FI 200-sec schedule.

In an FI performance, the time since reinforcement may function as one discriminable property of the many aspects of the experimental situation (*cf.* Skinner, 1938, Ch. 7). Times since reinforcement that are consistently correlated with nonreinforcement may come to control low rates of responding in much the same way as do other stimulus properties (*e.g.*, intensity, wavelength). Discriminable periods of nonreinforcement in FI schedules probably contribute to the fact that an FI schedule generally maintains a lower overall rate of responding than a VI schedule providing the same overall rate of reinforcement. For example, except for Pigeon 121 in Fig. 1, the overall rates of responding maintained by arithmetic VI schedules were consistently higher than the overall rates maintained by corresponding FI schedules in Fig. 17.

Despite the possibility of temporal control, the performances maintained by FI schedules do not appear to be as well under the control of time since reinforcement as the capacity of

the pigeon to discriminate durations would suggest (Reynolds and Catania, 1962; Reynolds, 1966; Stubbs, 1968). In an FI performance, responding occurs at appreciable rates even at times since reinforcement well before the opportunity for reinforcement at the end of the interval. Other factors presumably operate to attenuate temporal control in an FI schedule.

Fixed-interval reinforcement sets the occasion for the incidental but consistent correlation of responding at one time in an interval and subsequent reinforcement at the end of the interval. The early responding may be maintained by the later reinforcement (*cf.* Dews, 1962, who suggests that responding over time in an FI schedule reflects a delay-of-reinforcement gradient). Such delayed reinforcement must operate in conjunction with temporal discrimination: the time in the interval at which responding occurs must be to some extent discriminated if the responding is to be consistently controlled by the time that separates it from reinforcement at the end of the interval.

The incidental properties of the FI schedule may even produce effects in relatively trivial ways. For example, a decrease in response rate toward the end of an interval (Pigeon 68 at FI 200-sec, Fig. 16) may have its origin in an increase in the frequency with which the pigeon looked toward the feeder as the time approached when a response would operate the feeder.

Procedurally, the FI schedule is the simplest of the interval schedules but, paradoxically, the variables that appear to operate in FI schedules suggest that, in at least one respect, FI performance is more complex than VI performance. The FI schedule is at one extreme of a continuum of schedules that differ in the degree to which they allow discriminative control by time since reinforcement; at the other extreme is the constant-probability VI schedule, which simplifies performance by eliminating the temporal patterning of reinforcement as a controlling variable. The implication is that, although FI schedules show that effects of reinforcement extend over a considerable period of time since reinforcement, the contribution of FI performance to the quantitative analysis of VI schedules may not be simple and direct.

The next experiment explores the effects of combining two FI schedules. In terms of procedure, such a combination produces the simplest VI schedule, which consists of only two intervals, and permits further examination of the spread of the effects of reinforcement over the continuum of time since reinforcement.

EXPERIMENT 5: EFFECTS OF THE SEPARATION IN TIME OF OPPORTUNITIES FOR REINFORCEMENT IN TWO-VALUED INTERVAL SCHEDULES

This experiment addressed two separate but related questions. First, what is the effect of one probability of reinforcement on the local rate of responding maintained by a second probability as the period of time that separates them is varied? Second, what is the effect of the magnitude of their separation on the local rates of responding during the period of time between them?

The experiment compared the performance maintained by a single-valued interval schedule, FI 240-sec, with the performances maintained by several two-valued interval schedules. One interval in the two-valued schedules was 240-sec; the other was shorter (30, 90, 150, or 210 sec) and was presented with a relative frequency of 0.05 or 0.50. For example, in a two-valued schedule of 90-sec and 240-sec intervals with a relative frequency of 0.05 for the 90-sec interval, reinforcement was available 90 sec after the previous reinforcement in one of every 20 intervals and at 240 sec after reinforcement in the remaining intervals. According to the terminology of Ferster and Skinner (1957, Ch. 11), this schedule is a mixed FI 90-sec FI 240-sec schedule. The present purposes, however, require a specification not only of the durations of the scheduled intervals but also of their relative frequencies (*cf.* Millenson, 1959).

The proximity in time of the two opportunities in the two-valued schedules changed when the duration of the short interval was varied over the range from 30 to 210 sec. Thus, the temporal separation of the two opportunities was necessarily confounded with the time since reinforcement at which the earlier opportunity occurred.

METHOD

Subjects and Apparatus

Four adult, male, White Carneaux pigeons were maintained at 80% of free-feeding body weights. The key-pecking of each pigeon had previously been maintained by FI schedules of reinforcement for at least 40 hr.

The experimental chamber was similar to that described in Exp. 1. The schedules were arranged by stepping switches operated every 10 sec by an electronic timer and reset after each reinforcement. The stepping switches arranged reinforcement either after 240 sec (24 steps of the stepping switches) or, according to the scheduled occurrences of the shorter interval, at the time specified for this interval. Each interval began only after the 4-sec reinforcement at the end of the preceding interval. The stepping switches also served to distribute responses to 24 counters that represented the twenty-four 10-sec periods of time since reinforcement.

Procedure

The schedules and sessions for each pigeon are summarized in Table 4. In each two-valued interval schedule, the long interval was 240 sec. The table shows the duration of the short interval and its probability or relative frequency of occurrence, in rft/op. An entry of 240 sec indicates that no short interval was arranged.

Each daily session consisted of 21 reinforcements: reinforcement of the first response of the session, followed by 20 intervals. When the relative frequency of the short interval was 0.05, a single short interval occurred at a different place in the sequence of 20 intervals in each session. When the relative frequency of the short interval was 0.50, an irregular sequence of short and long intervals varied from one session to the next. The sequence never included more than four successive occurrences of either interval, and was balanced so that the relative frequencies of the short and long intervals were independent of the duration of the preceding interval.

The session durations varied from about 45 min (short interval of 30 sec with a relative frequency of 0.50, or mixed FI 30-sec FI 240-sec) to about 80 min (no short interval, or FI

Table 4

Sequence of two-valued interval schedules for each pigeon. Entries show the duration (sec) and relative frequency (rft/op) of the short interval. The long interval was held constant at 240 sec.

Pigeon									Sessions
85		86		34		35			
Short Interval	Rft/Op	Short Interval	Rft/Op	Short Interval	Rft/Op	Short Interval	Rft/Op		
240	1.00*	240	1.00*	240	1.00*	240	1.00*	40	
30	0.50	210	0.50	30	0.05	210	0.05	52	
30	0.05	210	0.05	90	0.05	150	0.05	102	
150	0.05	30	0.05	150	0.05	150	0.50	61	
240	1.00*	30	0.50	210	0.05	90	0.50	37	
240	1.00*	90	0.50	240	1.00*	90	0.05	39	
240	1.00*	240	1.00*	240	1.00*	240	1.00*	47	

*Fixed-interval schedule (FI 240-sec).

240-sec). The data presented are averages over the last five sessions of each schedule.

RESULTS

Local rates of responding. Figure 18 shows local rates of key-pecking as a function of time since reinforcement for Pigeon 34 in five interval schedules. The performance maintained by the single-valued schedule (FI 240-sec) is represented in the bottom panel (filled circles). The performances maintained by the two-valued schedules, which consisted of 240-sec intervals and a shorter interval, are represented in the top four panels. The relative frequency of the shorter interval, here equal to rft/op, was always 0.05 and its duration was 30, 90, 150, or 210 sec. Reading the graphs from top to bottom shows the effect of moving the end of the short interval from an early time after reinforcement up to coincidence with the end of the 240-sec interval. Differences in the performances were therefore due at least in part to changes in the time separating the probability of reinforcement of 0.05 from the terminal probability of 1.0. These differences were of two sorts. First, when the probability of 0.05 was at 30 sec, the rate of responding declined for some time before it increased as the terminal probability of 1.0 at 240 sec was approached, whereas when the probability of 0.05 was at 90, 150, or 210 sec, the rate of responding did not decline.

Second, the rate of responding maintained by the probability of 0.05 was lower the earlier it occurred or, in other words, the longer the period of time that separated it from the terminal probability at 240 sec. These two

variables, the time at which the probability of 0.05 occurred and its separation from the terminal probability, were confounded: the later the probability of 0.05, the less its temporal separation from the terminal probability. Data from Exp. 1 and 3, however, suggest that the temporal proximity of the terminal probability is the more relevant variable. In those experiments, increases in time since reinforcement generally produced decreases in the rate of responding maintained by a given probability. In the arithmetic VI schedule, for example, the response rate maintained by the probability of reinforcement at 1t sec decreased as t increased (the left-hand point on each function in Fig. 2, Exp. 1). Because this change in the local rate of responding maintained by a given probability with changes in its location in time was opposite to that obtained in the present experiment, the present findings cannot be attributed solely to the changes in the location in time of the probability of 0.05 in the two-valued interval schedules. A similar point can be made based on the FI data of Exp. 4 (Fig. 17, terminal rate).

Additional data are shown in Fig. 19. The data from Pigeon 86 (left column, upper three panels) show the effect of a probability of reinforcement of 0.50 at various times since reinforcement; the data from Pigeons 85 (left column, bottom panel) and 35 (right column) show the effect of a probability of 0.05 at various times. The responding maintained by the two-valued interval schedules (unfilled circles) is compared with that maintained by the one-valued schedule, FI 240-sec (filled circles).

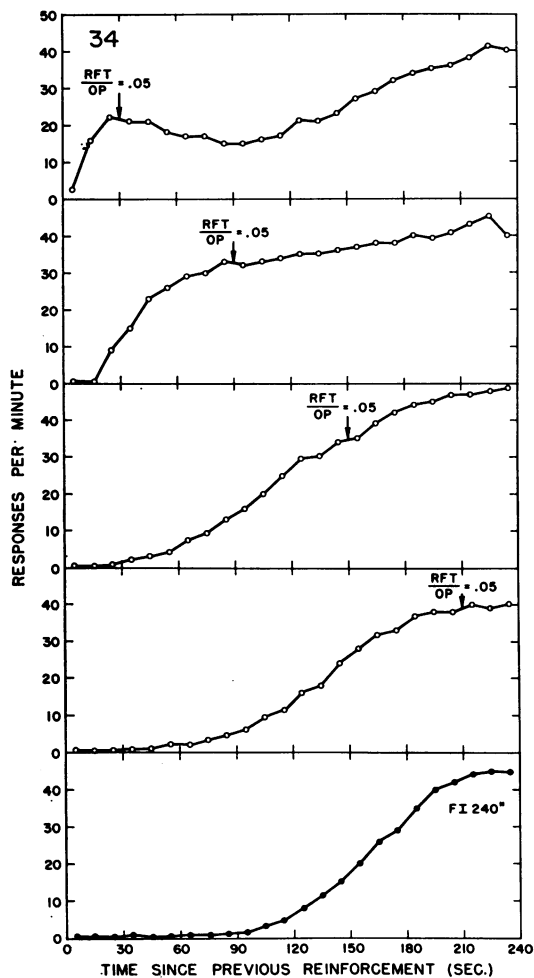


Fig. 18. Rate of key-pecking as a function of time since reinforcement in five interval schedules (Pigeon 34). With a probability (rft/op) of 0.05, a shorter interval was introduced into an FI 240-sec schedule at the times since reinforcement indicated by the arrows in the top four panels. The bottom panel shows the performance maintained by FI 240-sec without a shorter interval.

The local rate of responding maintained by the probability of 0.50 (Pigeon 86) at 30 sec was approximately equal to the rate maintained 210 sec later by the terminal probability at 240 sec. This is consistent with findings of Exp. 1 and 3 (Fig. 3, 7, and 8) which showed that a probability of reinforcement of 0.50 maintained about the same rate of responding as a probability of 1.0. The equality of the rates cannot be attributed to the closeness of the two probabilities in time, because they were separated by 210 sec and because within these 210 sec the local rate of responding decreased and then increased.

The local rates of responding maintained by the probabilities of 0.50 and 1.0 were also about equal when the probability of 0.50 was at 90 sec (left column, panel b), but there was little if any decrease in response rate between 90 and 240 sec. Finally, with the probability of 0.50 at 210 sec (panel c), the performance was scarcely distinguishable from that maintained by the FI 240-sec schedule.

The performance of Pigeon 85 partially confirms the conclusions drawn from the performance of Pigeon 34 (Fig. 18). The rate maintained by the probability of 0.05 was lower, relative to the terminal rate at 240 sec, when this probability occurred at 30 sec than when it occurred at 150 sec. Even when this probability occurred at 30 sec, however, the rate of responding did not decline during the time between this and the terminal probability of 1.0. The performance of Pigeon 35 (right column) was atypical in that the local rate of responding consistently passed through a maximum earlier than 240 sec after reinforcement, even in the FI 240-sec schedule. Nevertheless, the maximum in the local rate of responding maintained by the probability of reinforcement of 0.05 occurred later when this probability was moved from 90 to 150 sec (panels a and b), and the performance became more like that maintained by the FI 240-sec schedule when the probability was moved to 210 sec.

Figure 20 directly compares the responding maintained by a probability of reinforcement of 0.05 at 30 sec after reinforcement and the responding maintained by a probability of 0.50 at the same time after reinforcement (data from Pigeon 85). Relative to the performance maintained by FI 240-sec (filled circles), the probability of 0.05 produced an increase in the local rate of responding at 30 sec. This rate was considerably lower than that at 240 sec, when the probability became 1.0. The probability of 0.50 produced a relatively higher response rate at 30 sec and the rate increased slightly throughout the remainder of the interval. This is consistent with the findings of Exp. 1 and 3 (Fig. 3, 7, and 8), in that the rate of responding maintained by a probability of 0.05 was low relative to that maintained by a probability of 0.50.

When the two intervals, 30 sec and 240 sec, occurred with equal relative frequencies for Pigeon 85, they maintained a performance

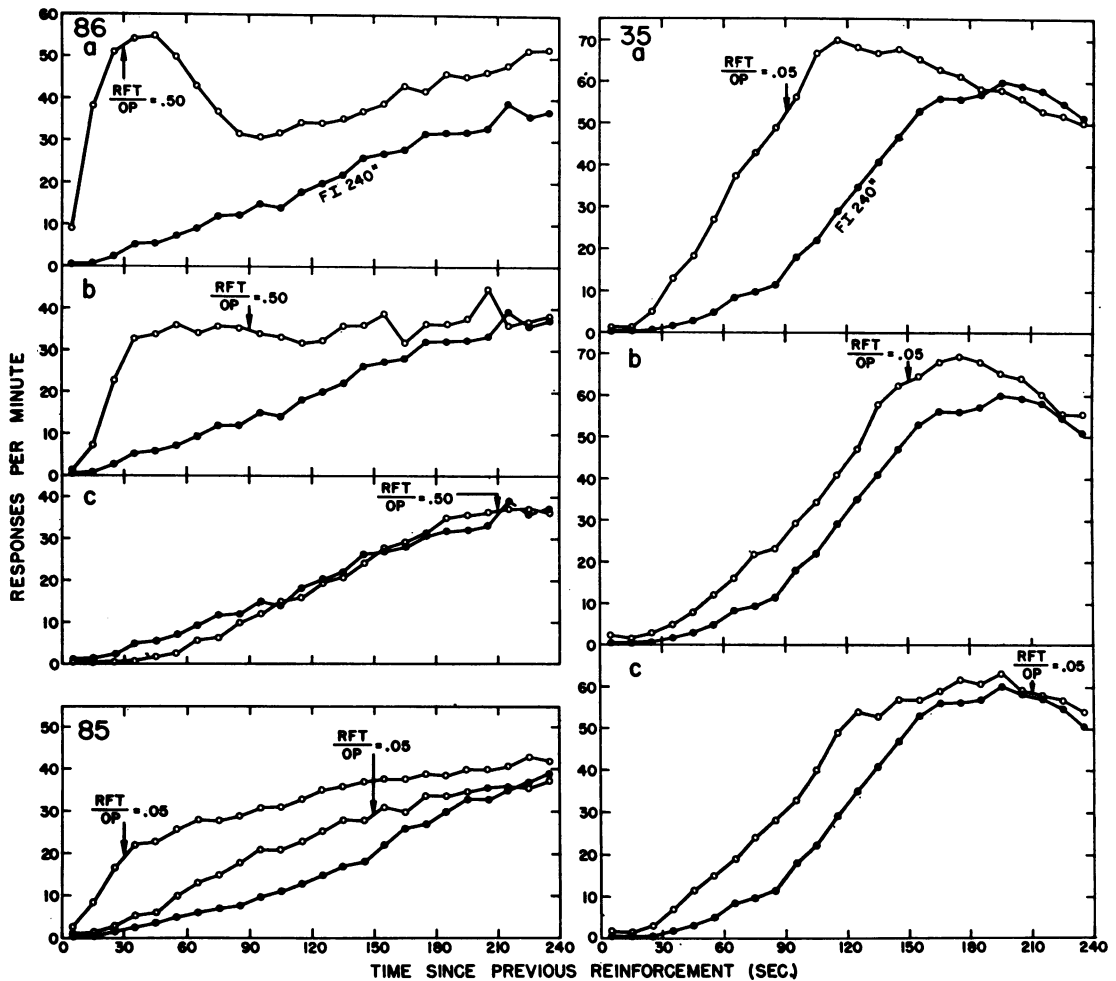


Fig. 19. Rate of key-pecking as a function of time since reinforcement (Pigeons 86, 85, and 35). Filled circles show the performance maintained by an FI 240-sec schedule. Unfilled circles show the performances maintained when a shorter interval was introduced with the probabilities (rft/op) and at the times since reinforcement indicated by the arrows.

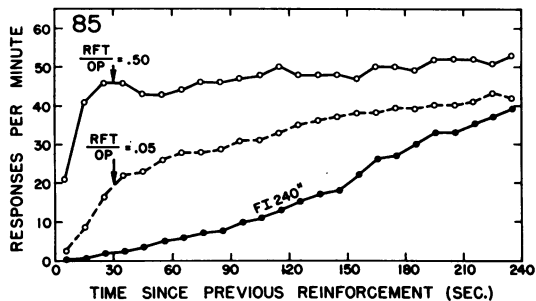


Fig. 20. Rate of key-pecking as a function of time since reinforcement in three interval schedules (Pigeon 85). Filled circles show the performance maintained by an FI 240-sec schedule. Unfilled circles show the performances maintained when an interval of 30 sec was introduced with a probability (rft/op) of 0.05 or 0.50 into the FI schedule.

that was, over most of the range of time after reinforcement, similar to those maintained by some of the VI schedules examined in Exp. 1 and 3. Thus, two-valued interval schedules can sometimes sustain responding over a considerable period after reinforcement as effectively as can many-valued (VI) schedules. Similar findings have been discussed by Millenson (1959), who examined a mixed FI 30-sec FI 120-sec schedule in which the relative frequency of the shorter interval was 0.40. These data may indicate that different probabilities of reinforcement (e.g., 0.05 and 0.50) vary in the extent to which their effects spread in time.

A comparison of the probabilities of 0.05 and of 0.50 at four different times after rein-

forcement is shown in Fig. 21 (data from Pigeons 86 and 35). At 30 sec, the difference between the rates of pecking maintained by these two probabilities was considerable (Pigeon 86, lower left panel). This pigeon's rate of responding, unlike that of Pigeon 85 in Fig. 19, decreased before again increasing during the time from 30 to 240 sec. A difference in the effects of the two probabilities was also evident at 90 sec (Pigeon 35, upper left panel) and, to a lesser extent, at 150 sec (Pigeon 35, upper right panel). At 210 sec (Pigeon 86, lower right panel), both probabilities maintained rates of responding about equal to those maintained 30 sec later, at 240 sec.

Overall rates of reinforcement. The introduction of short intervals increased the overall rate of reinforcement relative to the 15 rft/hr provided by the single-valued FI 240-sec schedule. The probability of 0.50 at the end of the short interval made available rates of reinforcement ranging from 16 (short in-

terval of 210 sec) to 26.7 (short interval of 30 sec) rft/hr. The probability of 0.05 at the end of the short interval, however, made available only 15.1 (short interval of 210 sec) to 16 (short interval of 30 sec) rft/hr. To some extent, the changes in the overall rates of responding maintained by these schedules may have been determined by these changes in the overall rate of reinforcement. The changes in overall rate of responding, however, were not consistent with those predicted from the general form of the functions of Exp. 1 (Fig. 1) and therefore must have depended at least in part on the changes in the distribution of intervals in time. This is particularly the case for the probability of 0.05, for which a change in rft/hr of only about 6% (from 15 to 16 rft/hr) produced 50% to 90% increases in overall rates of responding.

Cumulative records. The relative consistency of the performances maintained within individual intervals by VI schedules (Fig. 4

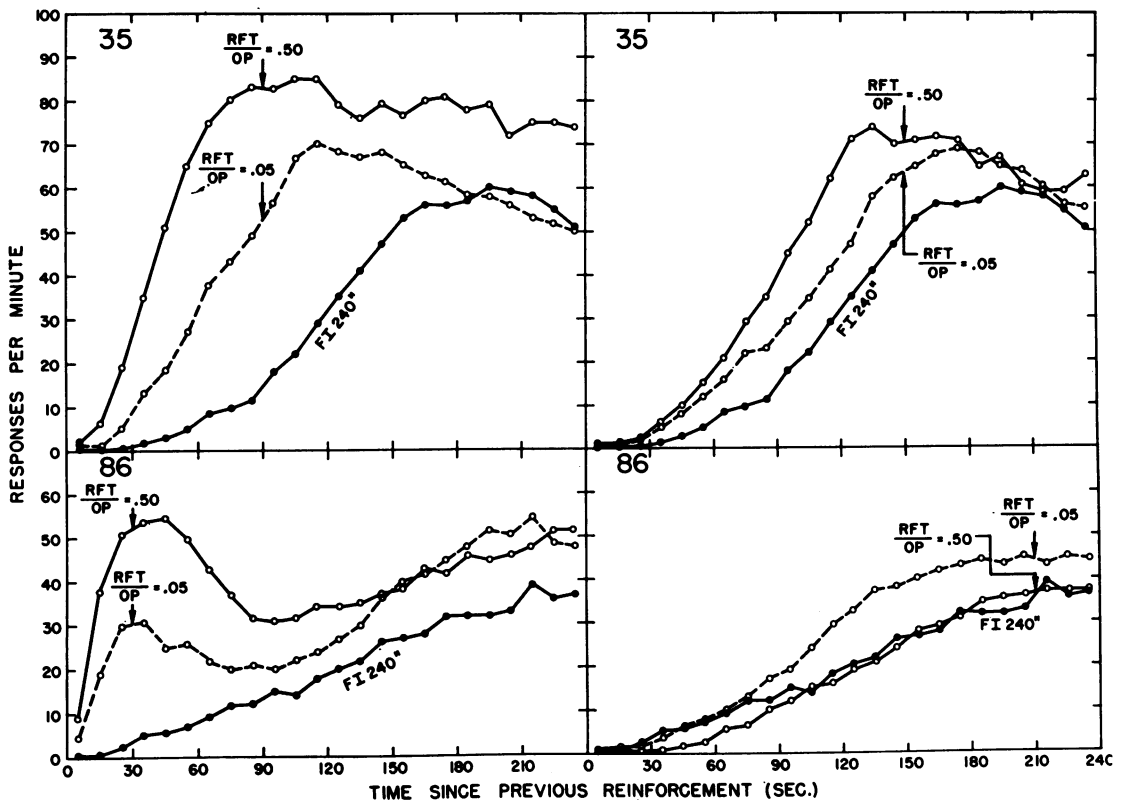


Fig. 21. Rate of key-pecking as a function of time since reinforcement (Pigeons 35 and 86). Filled circles show the performance maintained by an FI 240-sec schedule. Unfilled circles show the performances maintained when a shorter interval (30, 90, 150, or 210 sec) was introduced with a probability (rft/op) of 0.05 or 0.50 into the FI schedule.

and 13) was not a characteristic of the FI 240-sec and the mixed FI FI schedules of the present experiment. Figure 22 shows cumulative records of the performance of Pigeon 86 in five of the present schedules, and indicates that the average rates of responding illustrated in Fig. 18 through 21 are not necessarily representative of responding within individual intervals. The performance maintained by FI 240-sec, for example, in the top record of Fig. 22, is fairly typical of the variability in output from interval to interval in FI performances as reported by Ferster and Skinner (1957), among others. The temporal patterning of responding also varied considerably from interval to interval. A fairly constant rate of responding was maintained throughout most of some intervals in the record, for example, whereas a gradually increasing rate of responding was observed in other intervals.

The record illustrating the performance maintained with a probability of 0.05 at 30 sec shows that a transition from a high to a low rate followed by a return to a higher rate occurred in most intervals of the schedule. Intervals in which this pattern was absent tended to occur early in the session. Again, the record indicates that the smoothness of the average curve in Fig. 21 was not representative of the performances in individual intervals. Slow changes in local rates of responding were observed, as in the second full interval after the short interval in the illustrative record, but rather abrupt transitions from a fairly high rate to an almost zero rate followed by a return to a higher rate were also fairly common, as in the next-to-last interval of the record.

This pattern of responding, in which the rate decreased and then increased within in-

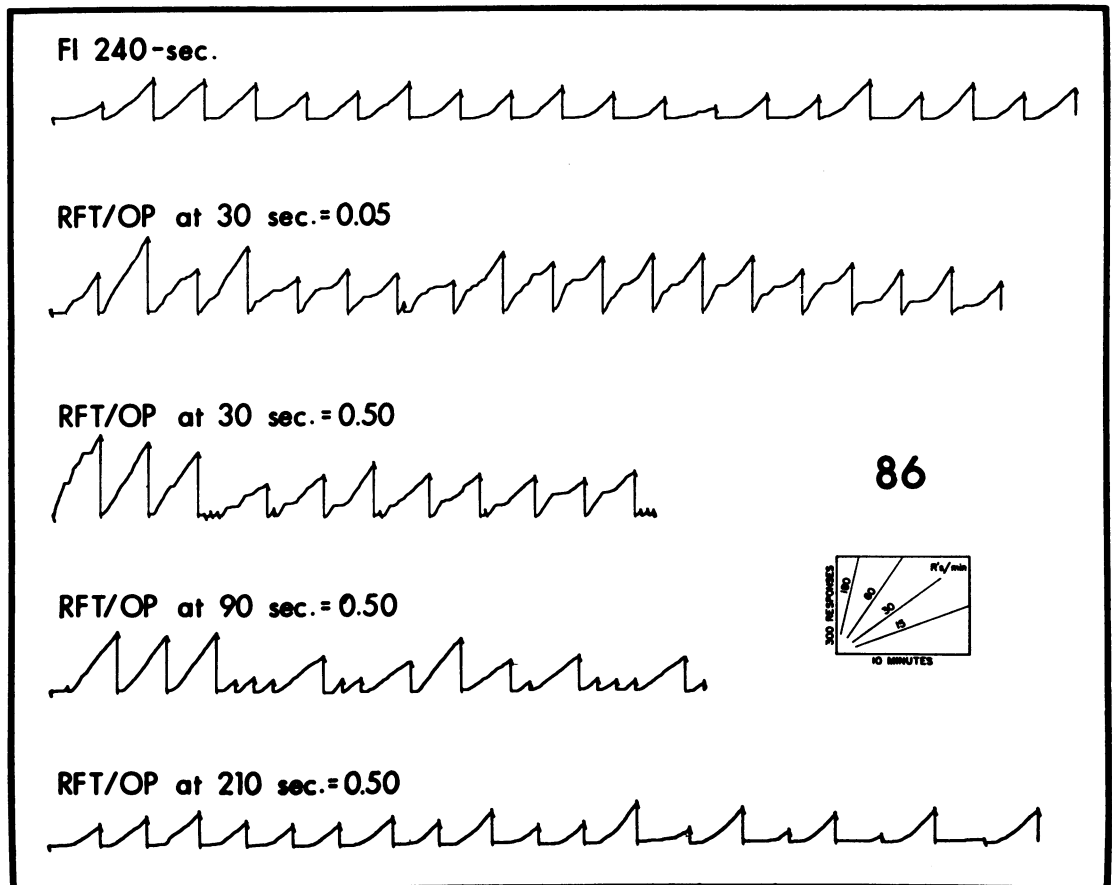


Fig. 22. Cumulative records of full sessions of Pigeon 86's key-pecking maintained by an FI 240-sec schedule and by four schedules in which a shorter interval (30, 90, or 210 sec) was added with a probability (rft/op) of 0.05 or 0.50. The recording pen reset to baseline after each reinforcement, indicated by diagonal pips.

dividual intervals, also occurred when the probability at 30 sec was raised to 0.50, as illustrated by the third cumulative record. Within this schedule, however, the performance from interval to interval seemed somewhat more variable and, again, the temporal patterning was typically absent in the early intervals of the session.

When the probability of 0.50 was moved to 90 sec (fourth record), a fairly uniform rate of responding was maintained within each interval, consistent with the average data presented in Fig. 19 (86b). Although this pattern of responding was fairly regular, the particular rate of responding maintained throughout each interval tended to vary from interval to interval.

When the probability of 0.50 was moved to 210 sec (fifth record), the performance became more like that maintained by FI 240-sec (see Fig. 19, 86c, and Record 1 of Fig. 22), with perhaps somewhat more variability in the total output from interval to interval than was maintained by the FI schedule.

DISCUSSION

When the two probabilities of reinforcement in the two-valued schedules were separated by a considerable period of time, the probability of 0.05 at the end of the short interval maintained lower local rates of responding than did the probability of 1.0 at the end of the long interval. The difference between the local rates maintained by the two probabilities became smaller as the two probabilities moved closer in time. The probability of 0.50 at the end of the short interval, on the other hand, maintained about the same local rate of responding as the later probability of 1.0 even when the temporal separation of the two probabilities was large. The findings are consistent with the effects of different probabilities of reinforcement in the VI schedules of Exp. 1 and 3. The exceptions to these generalizations again demonstrate the consistency of individual differences among pigeons. For each of the schedules studied with Pigeon 35, for example, the local rate of responding passed through a maximal value at some time before the end of the 240-sec interval (Fig. 19 and 20), a characteristic of performance not noted for the other pigeons.

To some extent, the performances maintained by the present schedules can be

considered simple combinations of the performances separately maintained by the component FI schedules. Compare, for example, Pigeon 69 (Fig. 16) and Pigeon 86 (Fig. 19), whose performances on FI 200-sec and FI 240-sec, respectively, were similar in both absolute level and the temporal patterning of responding. Data for Pigeon 69 show local rates of responding maintained separately by intervals of 30 and 200 sec (Fig. 16, left); data for Pigeon 86 show local rates of responding maintained by almost the same intervals, 30 and 240 sec, in combination (Fig. 19, upper left). The agreement between the two sets of data is fairly good, when it is considered that reinforcement at 30 sec was arranged with a probability of 1.0 for Pigeon 69 and 0.50 for Pigeon 86, and that the FI 30-sec schedule for Pigeon 69 necessarily prohibited responding after 30 sec since reinforcement. Some differences include the lower local rates of responding shortly after reinforcement in the FI 30-sec schedule for Pigeon 69 than in the two-valued schedule for Pigeon 86, and the somewhat larger difference between the terminal rates in the two FI schedules for Pigeon 69 than between the rates at the end of the two intervals in the schedule for Pigeon 86 (*cf.*, however, the later performance of Pigeon 86 in the same schedule: Fig. 23, Exp. 6). Greater disagreement can be found by making the same kind of comparison between the FI data for Pigeon 69 and the corresponding data for Pigeon 85 (Fig. 20, $rft/op = 0.50$). Pigeon 85 differed from Pigeon 86 primarily in the higher local rates of responding maintained between the two opportunities for reinforcement in the two-valued schedule.

The relevance of the present findings to the analysis in terms of local rates of reinforcement in Exp. 3 lies mainly in their indication of the extensive period of time since reinforcement over which a particular probability of reinforcement can have its effect (*cf.* Exp. 4), and of the degree to which a later high probability of reinforcement can influence the local rate of responding maintained by an early low probability of reinforcement (*e.g.*, $rft/op = 0.05$). The calculation of local rates of reinforcement described in Exp. 3 (Fig. 6) contributes little to the analysis of the two-valued schedules. By this calculation, the local rate of reinforcement remains constant at the end of the short interval and increases

about seven-fold at the end of the long interval as the short interval is moved from 30 to 210 sec since reinforcement. This inconsistency with the observed local rates of responding in the schedules again demonstrates the limited applicability of the method of calculating local rates of reinforcement.

EXPERIMENT 6: EFFECTS OF THE OMISSION OF REINFORCEMENT AT THE END OF THE LONG INTERVAL IN TWO- VALUED INTERVAL SCHEDULES

Experiment 5 suggested that the responding at and near the end of the short interval in two-valued interval schedules is maintained not only by reinforcement at the end of the short interval but also by reinforcement at the end of the long interval. The present experiment examined the role of the long interval in two-valued interval schedules by substituting timeout, an event that generally does not serve as a reinforcer, for reinforcement at the end of the long interval.

METHOD

The two-valued FI schedules of Exp. 5 were modified by substituting a 4-sec period of timeout (no key light or house light) for the 4-sec reinforcement at the end of the 240-sec interval. Reinforcement remained available for the first response of each session and at the end of the short interval. Table 5 summarizes the procedure and indicates the duration and relative frequency of the short intervals for each pigeon. When reinforcement was available at 240 sec (conditions 1 and 4 in Table 5), details were the same as in Exp. 5;

each session consisted of 21 reinforcements. With timeout substituted for reinforcement at 240 sec (conditions 2 and 3 in Table 5), sessions consisted of 20 intervals: two reinforcements per session when the short interval occurred with a relative frequency of 0.05 (reinforcement of the first response of the session and at the end of the single short interval), and about 11 reinforcements per session when the short interval occurred with a relative frequency of 0.50 (reinforcement of the first response of the session and at the end of about 10 short intervals).

During the first 25 sessions of the second condition, timeout was produced by the first response after the end of the 240-sec interval. Thereafter, timeout occurred independently of responses at the end of the 240-sec interval.

RESULTS

For each pigeon, Fig. 23 shows the local rates of responding maintained by a probability of reinforcement of 0.50 when a response was reinforced with a probability of 1.0 at 240 sec (filled circles) and when timeout occurred at 240 sec (unfilled circles). The schedules with reinforcement at 240 sec maintained performances roughly comparable to those maintained by the equivalent schedules in Fig. 5. One exception, in the performance of Pigeon 86, was that the local rate of responding maintained by the probability of 0.50 at 30 sec was considerably higher than the rate maintained by the higher probability of 1.0 at 240 sec (Fig. 19, 86a).

The substitution of a 4-sec timeout for the 4-sec reinforcement had only small effects on local rates of responding. For all pigeons, the local rate of responding immediately after

Table 5

Sequence of interval schedules for each pigeon. Entries show the relative frequency (rft/op) of the short interval (in sec). The terminal event at 240 sec was either reinforcement of a response (Rft) or a 4-sec timeout (TO).

Pigeon	85	86	34	35	
Short Interval	30	30	90	90	
Terminal Event (240-sec)	Rft/Op	Rft/Op	Rft/Op	Rft/Op	Sessions
1. Rft	0.05	0.50	0.05	0.50	44
2. TO	0.05	0.50	0.05	0.50	57*
3. TO	0.50	0.05	0.50	0.05	54
4. Rft	0.50	0.05	0.50	0.05	41

*The 4-sec timeout was response-dependent during the first 25 sessions and response-independent thereafter.

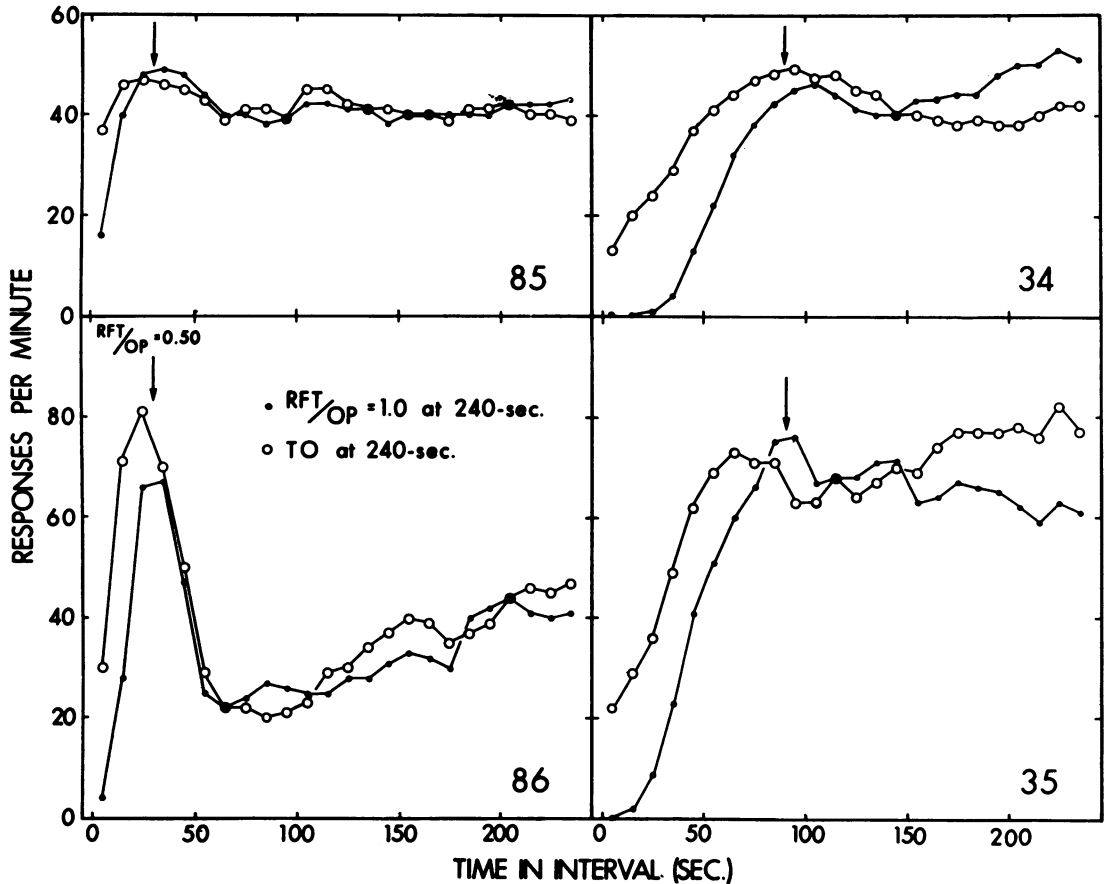


Fig. 23. Rate of key-pecking as a function of time since the start of an interval, for four pigeons. In one schedule (filled circles), reinforcement was available at 240 sec. In the other schedule (unfilled circles), a response-independent 4-sec timeout (TO) was presented at 240 sec. In both schedules, reinforcement was available with a probability (rft/op) of 0.50 at either 30 (Pigeons 85 and 86) or 90 (Pigeons 34 and 35) sec after the start of an interval.

timeout (early times in each interval) was higher than the rate in the equivalent schedules with reinforcement at 240 sec. Local rates of responding after the end of the short interval ($rft/op = 0.50$) were fairly similar in the two types of schedules. One factor that may have contributed to the small effect of substituting timeout for reinforcement was that even with timeout at 240 sec reinforcement occasionally followed 30 or 90 sec later (in the short interval). This does not seem to account for the higher local rates early in intervals, however, because rates of responding immediately after timeout were, for Pigeons 86, 34, and 35, lower than local rates of responding immediately preceding timeout (initial and terminal local rates). An alternate possibility is that timeout did not fully acquire control as a temporal reference point

for subsequent responding within intervals, so that the substitution of timeout for reinforcement produced higher local rates of responding early in intervals. In the preceding experiments, the durations of intervals had been timed consistently from a preceding reinforcement. The effects, however, were evident in the performances of Pigeons 85 and 34, for which the data presented are based on over 100 sessions with timeout at 240 sec, as well as in the performances of Pigeons 86 and 35. Finally, since timeout is sometimes followed by relatively high rates of responding in interval schedules, the rise in local rate early in intervals may reflect a direct effect of timeout on subsequent responding (*e.g.*, Ferster, 1958; Neuringer and Chung, 1967).

Figure 24 compares, for each pigeon, the performances maintained with reinforcement at

240 sec (unfilled circles) and with timeout at 240 sec (unfilled circles) when the probability of reinforcement at the end of the short interval was 0.05. Again, with the exception of the elevated local rate of responding at 30 sec for Pigeon 86, the performances maintained by the schedules with reinforcement at 240 sec were roughly comparable to the equivalent performances in Exp. 5. When timeout was substituted for reinforcement at 240 sec, however, the schedules lost control over the distribution of responses in time. In other words, a relatively low and constant local rate of responding was maintained, independent of the time elapsed in the interval. For Pigeons 85 and 34, the local rate of responding was about equal to the local rate maintained by the probability of 0.05 with reinforcement at 240 sec. For Pigeons 86 and 35, the local rate of responding was considerably lower

than the local rate maintained by the probability of 0.05 with reinforcement at 240 sec. The low local rates of responding, however, do not represent a stable and relatively continuous low rate of responding, but rather an average over higher rates of responding alternating irregularly with long periods of no responding. Thus, the probability of 0.05, unlike the probability of 0.50, was less effective in maintaining responding when the higher probability of reinforcement at a later time was removed. In other words, the rate of responding maintained by the probability of 0.05 probably was supported in part by the probability of 1.0 at 240 sec.

DISCUSSION

When reinforcement was eliminated at 240 sec, the temporal pattern of responding was maintained when the earlier probability was

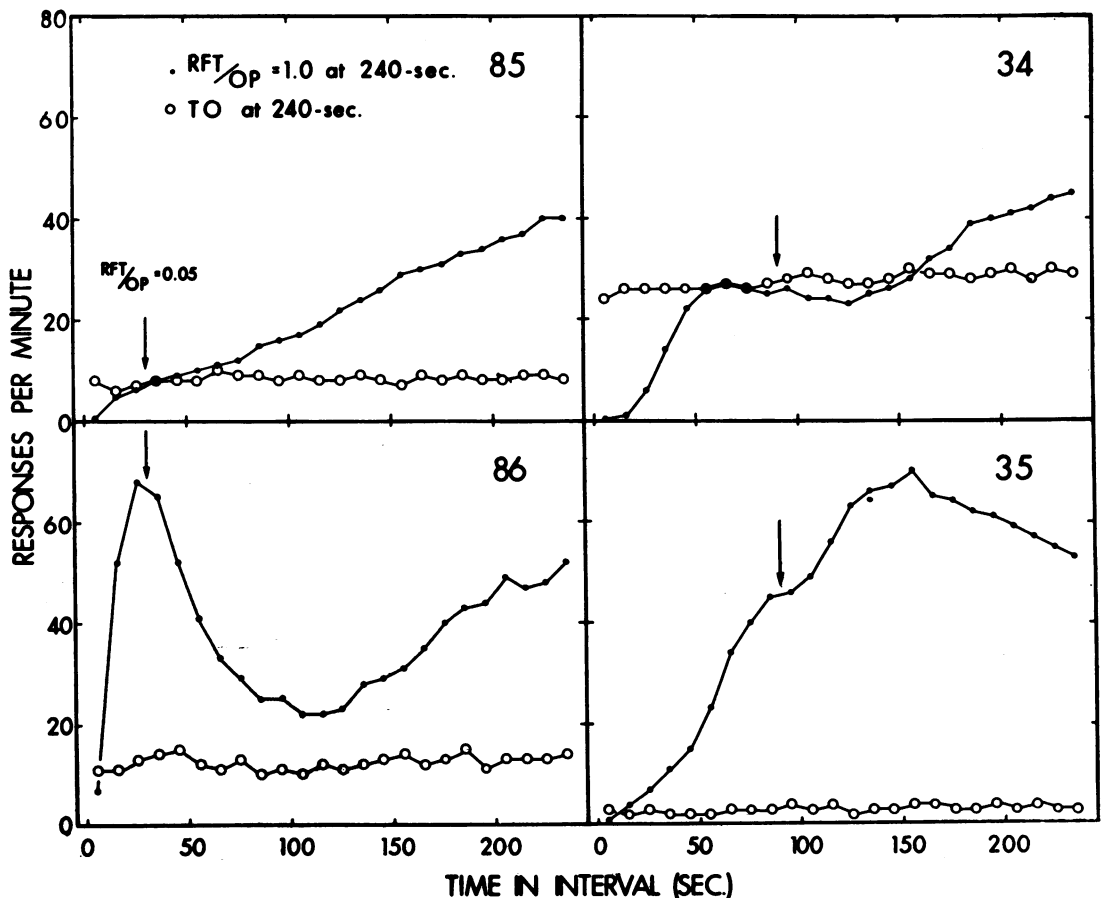


Fig. 24. Rate of key-pecking as a function of time since the start of an interval, for four pigeons. Same as Fig. 23, except that reinforcement at either 30 (Pigeons 85 and 86) or 90 (Pigeons 34 and 35) sec after the start of the interval was available with a probability (rft/op) of 0.05.

0.50, but not when the earlier probability was 0.05. It is possible that the temporal pattern could have been maintained by the probability of 0.05 under different circumstances. The elimination of reinforcement at 240 sec not only changed the stimulus from which intervals were timed, but also, when the earlier probability was 0.05, drastically decreased the overall rate of reinforcement. Responding might have been maintained more consistently at and near the end of the short interval if the probability at 240 sec was gradually rather than abruptly reduced from 1.0 to zero or if, in the absence of reinforcement at 240 sec, a high probability at the end of the short interval (e.g., 0.90) was gradually reduced to 0.50 and then to 0.05. It may also be relevant that the number of intervals and number of reinforcements per session were relatively small, although the present results were obtained over a reasonably large number of sessions (*cf.* Method).

The finding that reinforcement at the end of a long interval may support the responding maintained by earlier opportunities for reinforcement has implications for the analysis of interval schedules in terms of local rates of reinforcement. The calculation of local rates of reinforcement should not be limited only to the opportunities for reinforcement within a particular schedule. Instead, the local rate of reinforcement at any time since reinforcement should be based on the opportunities that occur over an extended period of time, with the probabilities of reinforcement at the different opportunities weighted as a function of their proximity to the time in question. The period of time over which opportunities for reinforcement contribute to the local rate of reinforcement at a particular time probably should grow as a function of the absolute time since reinforcement. Local rates of reinforcement calculated for successive points of time since reinforcement, therefore, would be a kind of moving weighted average of the probabilities of reinforcement over successive overlapping ranges of time. Such a calculation would take into account some of the properties of the interaction of different probabilities of reinforcement and different times since reinforcement explored in Exp. 4, 5, and 6. But the formulation of the quantitative details, their application to the VI schedules of the earlier experiments,

and the coordination of the overall-rate functions from VI schedules with the local rates in FI and two-valued interval schedules are beyond the scope of this paper. In the present research, different pigeons served in different experiments, and the magnitude of the individual differences among pigeons suggests that such an analysis would not stand up well to comparisons across pigeons. For the present, then, the formulation in Exp. 3 must be considered a first approximation with its application limited to many-valued interval schedules.

GENERAL DISCUSSION

The present experiments examined the effects on responding of a variety of characteristics of interval schedules of reinforcement. Experiment 1 established that the overall rate of responding maintained by arithmetic VI schedules was a monotonically increasing, negatively accelerated function of the overall rate of reinforcement (Fig. 1). The local rate of responding at a given time since reinforcement was, correspondingly, a monotonically increasing, negatively accelerated function of the probability of reinforcement at that time (Fig. 3). Experiments 2 and 3 examined VI schedules with different distributions of intervals. Experiment 2 demonstrated that reinforcement of a response immediately after a preceding reinforcement affected responding over only a relatively short period of time since reinforcement. In Exp. 3, two VI schedules with extra short intervals arranged various probabilities of reinforcement at a fixed time early in interreinforcement intervals (Fig. 7 and 8), and a constant-probability VI schedule arranged a fixed probability at various times within interreinforcement intervals (Fig. 11 and 12). These schedules demonstrated that the effect of a given probability of reinforcement could be independent of the time since reinforcement at which it occurred, but another schedule in Exp. 3, the "linear" VI schedule, suggested that the effect of a given probability also depended on its proximity in time to other probabilities. The "linear" VI schedule separated different probabilities widely enough in time to change the relationship between rate of responding and probability of reinforcement (Fig. 9 and 10). These effects, plus data in the literature

on geometric and Fibonacci VI schedules, led to the conclusion that responding is not simply controlled by the probability of reinforcement at a particular time within an interval, but rather by the probability taken over a period of time or, in other words, by the local rate of reinforcement. Limitations on a preliminary formulation of the control by local rates of reinforcement were indicated by Exp. 4, 5, and 6. Experiment 4 examined fixed-interval schedules, Exp. 5 showed in detail the combined effects of two probabilities of reinforcement as a function of their values and their separation in time in two-valued schedules (mixed FI FI), and Exp. 6 demonstrated that reinforcement at the end of the longest interval in a two-valued schedule supported the responding maintained by an earlier opportunity for reinforcement. These experiments suggested that the period of time within which reinforcement could contribute to a particular local rate of responding was large relative to the time since reinforcement. The spread of the effect of reinforcement at one time since reinforcement to local rates of responding at other times could be interpreted in terms of a gradient of temporal generalization. The performance maintained by an FI schedule may reflect such a gradient, but by its nature the FI schedule can provide only one side of such a gradient: up to the time at which reinforcement is made available but not beyond that time. The elimination of reinforcement at the end of the long interval in the two-valued schedules of Exp. 6 might have provided, but in fact did not provide, complete gradients (see the performance of Pigeon 86 in Fig. 19, upper left, for a suggestive example of a gradient of responding around 30 sec since reinforcement in Exp. 5).

Despite the ubiquitous individual differences among pigeons, the monotonically increasing, negatively accelerated form of the input-output function for interval schedules was consistent with many aspects of the data from the several experiments. The form of the function implies that the overall rate of responding maintained by a particular overall rate of reinforcement may be critically determined by the distribution of intervals in a schedule. The overall rate of responding is a weighted average of local rates of responding, and local rates of responding depend on

local rates of reinforcement within intervals. If the distribution of intervals in a schedule is changed while the overall rate of reinforcement is held constant, the decrease in the local rate of reinforcement at one time after reinforcement must be accompanied by an increase at some other time after reinforcement. Because the local rate of responding is a negatively accelerated function of the local rate of reinforcement, the decreased local rate of reinforcement at one time will not necessarily be compensated, in rate of responding, by the increased local rate of reinforcement at some other time.

The dependence of overall rate of responding on the distribution of intervals is most easily demonstrated by the comparison of FI and VI schedules, as illustrated in Fig. 25. The FI schedule includes discriminable periods of time during which the local rate of reinforcement, as inferred from performance, is at or near zero (*e.g.*, the responding of Pigeon 34 between 0 and 90 sec in the FI 240-sec schedule: Fig. 18). Such performance, which results in a large proportion of time when low rates of responding occur during each interval, produces an overall rate of pecking lower than that maintained by a schedule that provides no discriminable periods of nonreinforcement (*e.g.*, the constant-probability VI schedule).

The overall rates of responding maintained by VI schedules are higher than those maintained by FI schedules that provide the same overall rate of reinforcement, except at 1800 rft/hr (VI or FI 2-sec), when the schedules approach continuous reinforcement and when responding is more appropriately treated as a series of latencies from reinforcement than as a rate. (A reversal may also occur at very low rates of reinforcement. For example, FI 24-hr may maintain higher rates of responding than VI 24-hr. *Cf.* Morse, 1966). It seems reasonable to assume that the random-interval (constant-probability) VI schedule, in which the correlation between probability of reinforcement and time since reinforcement is minimal, and the FI schedule, in which the correlation between probability of reinforcement and time since reinforcement is maximal, represent the full range of overall rates of responding, at each overall rate of reinforcement, that can be maintained by interval schedules of reinforcement. The

random-interval and arithmetic VI data are in fair agreement, suggesting that effects of the distribution of intervals on the overall rate of responding are small provided that opportunities for reinforcement are reasonably closely and uniformly spaced along the continuum of time since reinforcement. On the basis of Fig. 25, it is not possible to say whether or not the VI and FI functions have the same form, and the form of the FI function would in any case depend on the way in which it is a derivative of the more fundamental function relating local rates of responding and local rates of reinforcement.

APPENDIX I: ANALYSIS IN TERMS OF INTERRESPONSE TIMES

A number of accounts of the performances maintained by interval schedules of reinforcement have been concerned with the differential reinforcement of interresponse times, or IRTs (Skinner, 1938; Newman and Anger, 1954; Anger, 1956; Morse, 1966; Shimp, 1967). This section relates the present findings to IRT analyses in a treatment that is an alternative to, but is not necessarily incompatible with, the treatment developed in the main body of the paper.

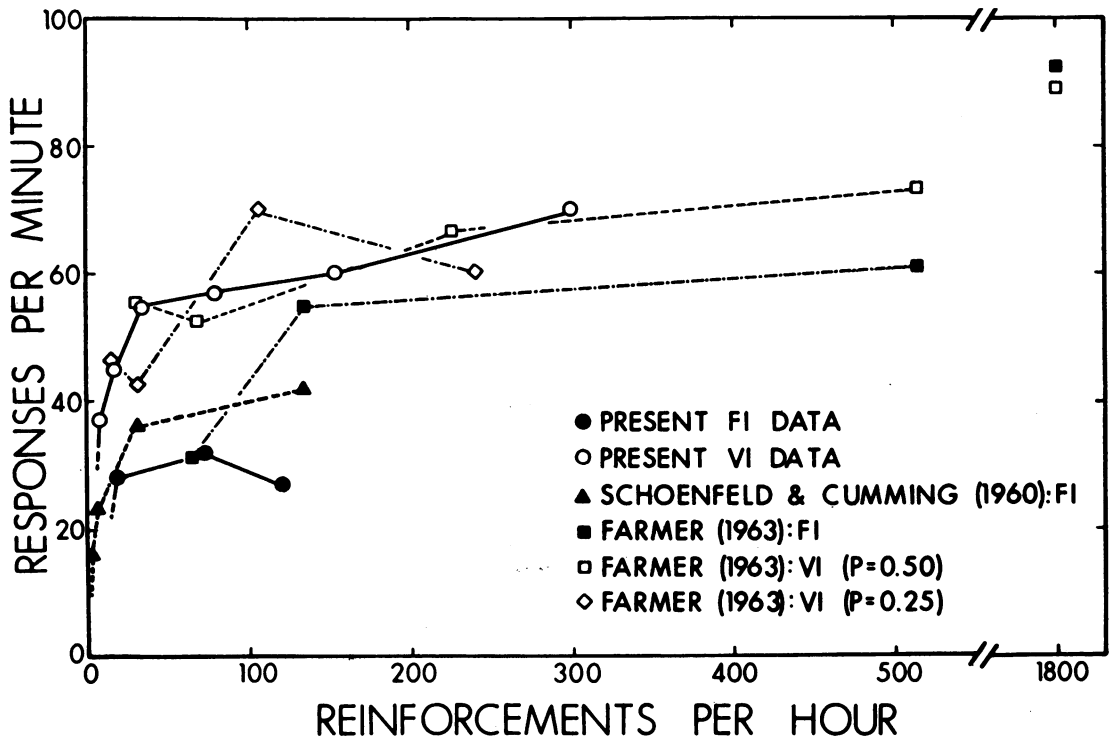


Fig. 25. Rates of pigeons' key-pecking as a function of the rates of reinforcement provided by FI and VI schedules. The present FI data are averaged across four pigeons (Fig. 17). The present VI data are averaged across six pigeons (Fig. 1); only the three VI schedules providing the highest rates of reinforcement were common to all six pigeons, so the average rates of responding on these three schedules were determined first, and the other rates were averaged only after they had been multiplied by a constant to adjust for the differences between birds in absolute levels maintained by the three common schedules. The FI data presented by Schoenfeld and Cumming (1960) come from different groups of two to four pigeons in different experiments (Hearst, 1958; Cumming and Schoenfeld, 1958; Clark, 1959), in all of which intervals were timed from the end of the preceding interval, rather than from the preceding reinforcement, and in which reinforcement, once arranged, was held available only for a time equal to the duration of the FI (limited hold). The FI and VI data from Farmer (1963) are averages across either two or three different pigeons at each point. Farmer arranged random-interval schedules (*cf.* Discussion, Exp. 3, or Appendix II) in which the probability of reinforcement, P , in each recycling time interval, T , was 1.0 (FI) or a lower value (VI). In each of Farmer's groups, T was constant and P was varied. Data were selected from Farmer's groups so that P was constant and T varied and therefore the distributions of intervals were comparable within each set of connected points.

An IRT is the time separating two consecutive responses; the first response initiates the IRT, and the second terminates it (technically, the boundaries of an IRT should be defined in terms of response onsets, but response durations will be assumed negligible for the present purposes). An IRT is said to be reinforced when the response that terminates it is reinforced. For a given IRT, therefore, the probability of reinforcement is the probability that responses will be reinforced when they terminate an IRT of this duration.

Within schedules of reinforcement, IRTs and latencies are sometimes not distinguished, but the distinction may be important. The first response after reinforcement terminates a latency, timed from the end of the reinforcement. This response does not terminate an IRT but, so long as it is not itself reinforced, it initiates the IRT terminated by the next response. In other words, two consecutive responses define the temporal boundaries of an IRT only if the first of the two responses is not reinforced. This logical distinction is consistent with the interpretation of reinforcement as an event that not only maintains responding but also provides a discriminative stimulus for subsequent responding. It may also have a bearing on the special characteristics of the earliest times after reinforcement (see Exp. 2).

The Probability of Reinforcement for an Interresponse Time

Figure 26 illustrates the probabilities with which different IRTs are reinforced in several schedules of reinforcement (*cf.* Anger, 1956, p. 152; Morse, 1966, p. 69). To emphasize differences among the schedules, the figure shows a considerable range of IRTs; in practice, the left-most portion is usually the most relevant, because the longer IRTs occur relatively infrequently in most schedules.

In an FI schedule, the probability of reinforcement varies linearly with IRT, reaching 1.0 at a duration equal to the fixed interval. Consider, for example, a 50-sec IRT in the FI 100-sec schedule illustrated in Fig. 26. This IRT will be reinforced only if it begins during the last 50 sec of the 100-sec interval, and its probability of reinforcement is therefore 0.5. No IRT can begin 100 or more sec after reinforcement in this schedule, because the

response that would initiate such an IRT would necessarily be reinforced.

This calculation of probabilities of reinforcement in an FI schedule assumes that, for any IRT, its distribution of starting times in the interval is uniform or rectangular, or, in other words, the probability that a given IRT will occur is independent of the time since reinforcement. This assumption usually is not satisfied within FI performances; for example, no 50-sec IRT would ever be reinforced if 50-sec IRTs never began after the first 25 sec of the 100-sec interval. The probabilities of reinforcement in Fig. 26, therefore, may be considered relative frequencies only with respect to all possible starting times of each IRT, and not necessarily with respect to actual relative frequencies in a particular FI performance. This observation imposes limitations on the present treatment, as discussed below, and indicates the importance of comparing recorded distributions of all IRTs with recorded distributions of reinforced IRTs; such data are not available for the present experiments.

When the availability of FI reinforcement is limited to a specified period of time (limited hold), the function relating probability of reinforcement to IRTs is altered for all IRTs longer than the limited hold, as illustrated in Fig. 26 by the 20-sec limited hold added to FI 100-sec. In that schedule, any IRT between 20 and 100 sec long will be reinforced only if it begins within a particular 20-sec period of time within the 100-sec interval; for these IRTs, therefore, the probability of reinforcement is 0.20. Any IRT of more than 120 sec cannot end before the limited hold is over and so cannot be reinforced. (The effects of reinforcement available in the next interval, after the limited hold is over, have been ignored in this computation.)

The effect of a limited hold on performance is similar to the effect of a ratio schedule (Ferster and Skinner, 1957; Morse, 1966), and in a ratio schedule as in an interval schedule with limited hold, the probability of reinforcement is constant over a considerable range of IRTs. The variable-ratio and fixed-ratio schedules in Fig. 26 show that when every tenth response on the average is reinforced (VR 10) or when exactly every tenth response is reinforced (FR 10), the probability of reinforcement is 0.10 and is indepen-

dent of IRT (assuming numerical positions of IRTs within the ratio can be ignored).

An FI schedule provides differential reinforcement for long IRTs, in that the probability of reinforcement is higher for long than for short IRTs. Such differential reinforcement is arranged more explicitly in a DRL (differential-reinforcement-of-low-rate) schedule. In the DRL schedule illustrated in Fig. 26, the probability of reinforcement is zero for IRTs shorter than 100 sec and 1.0 for IRTs equal to or longer than 100 sec.

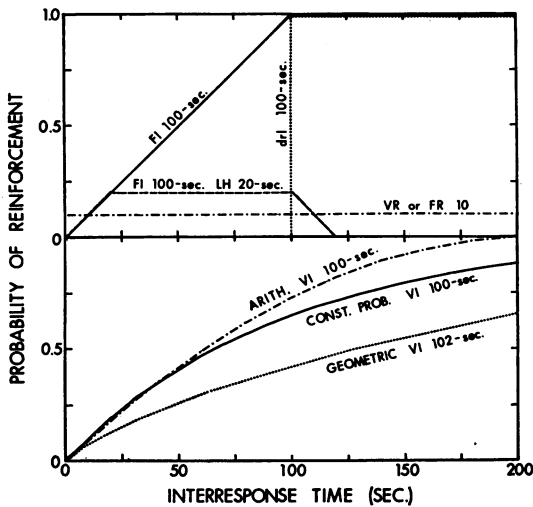


Fig. 26. Probability of reinforcement as a function of interresponse time in several schedules of reinforcement. The upper frame shows the functions for fixed-interval (FI 100-sec), fixed-interval with limited hold (FI 100-sec LH 20-sec), variable-ratio (VR 10) and fixed-ratio (FR 10), and reinforcement of all responses terminating interresponse times that exceed a minimum value (DRL 100-sec). The lower frame shows the functions for three different types of VI schedules: arithmetic, constant-probability, and geometric.

In VI schedules, the relationship between IRTs and their probabilities of reinforcement depends on the distribution of interreinforcement intervals. Figure 26 (bottom frame) shows illustrative functions for three VI schedules with roughly equal mean intervals: an arithmetic VI schedule (11 intervals from 0 to 200 sec, with an additive constant of 20 sec); a geometric VI schedule (10 intervals from 1 to 512 sec, with a multiplicative constant of 2); and a constant-probability VI schedule (in which, at the end of successive 10-sec periods of time since reinforcement, reinforcement is scheduled with a probability,

rft/op, of 0.10; cf. Exp. 3 and Appendix II).

The probabilities of reinforcement for IRTs in the arithmetic and geometric schedules in Fig. 26 were calculated by dividing all starting times of an IRT such that the IRT would be reinforced by all possible starting times of the IRT. Consider, for example, a 10-sec IRT in the arithmetic schedule. This IRT cannot occur in the 0-sec interval, in which the first response after reinforcement is reinforced. It will be reinforced if it begins during the last 10 sec of any of the 10 other intervals, from 20 to 200 sec; the sum of all reinforced starting times, therefore, is 100 sec. The IRT can begin at any time within an interval; the sum of all possible starting times, therefore, is the sum of all intervals, or $0 + 20 + 40 + \dots + 200 = 1100$ sec. Thus, the probability of reinforcement for the 10-sec IRT is 100 sec divided by 1100 sec, or 0.091.

Correspondingly, the reinforced starting times of a 10-sec IRT in the geometric schedule consist of the 1-, 2-, 4-, and 8-sec intervals plus the last 10 sec of each of the six longer intervals, or 75 sec; all possible starting times consist of the sum of the intervals, or $1 + 2 + 4 + \dots + 512 = 1023$ sec. Thus, the probability of reinforcement for the 10-sec IRT is 75 sec divided by 1023 sec, or 0.073.

The constant-probability schedule, as specified, does not consist of a finite number of intervals over which all reinforced starting times and all possible starting times of an IRT can be summed. The probabilities of reinforcement for IRTs, however, can be derived from the probability of reinforcement (rft/op) of 0.10 at the end of each 10-sec period of time since reinforcement. For example, any 10-sec IRT must end at or after the end of one 10-sec period and before the end of a second 10-sec period. Its probability of reinforcement, therefore, is 0.10. On the assumption of a uniform distribution of starting times for each IRT, the probability of reinforcement for all IRTs of less than 10 sec increases linearly with IRT from 0 to 0.10. A 5-sec IRT, for example, can begin during the first 5 sec or the last 5 sec of a given 10-sec period, and its probability of reinforcement, therefore, is 0.50 times 0.10, or 0.05.

For IRTs longer than 10 sec, the probability that reinforcement had become available at the end of either of two consecutive 10-sec

periods must be taken into account. For a 20-sec IRT, for example, this probability is 0.19; the probability of 0.10 at the end of the first 10-sec period plus the conditional probability, 0.90 times 0.10, at the end of the second 10-sec period. Again, the probabilities of reinforcement increase linearly, from 0.10 for a 10-sec IRT to 0.19 for a 20-sec IRT. (If a 10-sec limited hold were added to the schedule, as in the random-interval schedules of Farmer, 1963, the probability of reinforcement would remain constant at 0.10 for all IRTs longer than 10 sec).

A comparable procedure for calculating probabilities of reinforcement for IRTs could have been used for the arithmetic and geometric schedules, but would have been more complicated because of the different probabilities of reinforcement (rft/op) at each opportunity in those schedules. The VI functions in Fig. 26 appear to be smooth curves, but each is actually made up of linear segments. Changes in slope occur at IRTs equal to the durations of the intervals in a given schedule.

For IRTs up to about 40 sec, the probabilities of reinforcement in Fig. 26 are slightly higher in the constant-probability schedule than in the arithmetic schedule. For longer IRTs, the probabilities become higher in the arithmetic than in the constant-probability schedule. The probabilities in the geometric schedule are consistently the lowest. As mentioned above, the shorter IRTs are most significant in analyzing performance because the longer IRTs occur relatively infrequently.

The comparisons in Fig. 26 may imply that overall rates of responding maintained by a given overall rate of VI reinforcement should be slightly higher in constant-probability schedules than in arithmetic schedules and lowest in geometric schedules, but they neglect the possible role of different starting times of IRTs. Thus, they do not contribute to an account of how local rates of responding increase with time since reinforcement in arithmetic schedules, decrease in geometric schedules, and remain roughly constant in constant-probability schedules (Exp. 3).

The Probability of Reinforcement for Interresponse Times as a Function of Time Since Reinforcement

For an IRT that begins within a particular period of time since reinforcement in an

interval schedule, its probability of reinforcement is given by two independent probabilities: the probability that the IRT will end at or after an opportunity for reinforcement and the probability of reinforcement at that opportunity (rft/op). The former can be calculated on the assumption of a uniform distribution of starting times of the IRT within the period of time considered; the latter can be calculated from the distribution of intervals in the schedule.

With time since reinforcement as a parameter, Fig. 27 shows the probability of reinforcement for IRTs in the three VI schedules and the FI schedule of Fig. 26. The periods of time represented for the arithmetic and geometric VI schedules are those between successive opportunities for reinforcement.

In the constant-probability VI schedule, the probability of reinforcement at each opportunity is, by definition, independent of whether reinforcement became available at the previous opportunity. The probabilities of reinforcement for IRTs, therefore, also remain independent of time since reinforcement. (For the constant-probability schedule illustrated, this is true as long as the probabilities are calculated over periods of at least 10 sec. For example, if the first and second 5 sec after reinforcement were considered separately, the function for the first 5 sec would be displaced to the right in Fig. 27, to begin at an IRT of 5 sec; the function for the second 5 sec would be the same as that in the figure.)

Within each period of time in the arithmetic schedule, the probability of reinforcement increases linearly from 0 to 1.0 with increasing IRT. The later the time since reinforcement, the steeper the function. In other words, for a given IRT (vertical cut through the functions), the probability of reinforcement increases as time passes since reinforcement. Or, for a given probability of reinforcement (horizontal cut through the functions), the IRT reinforced with that probability becomes shorter as time passes since reinforcement.

The broken line superimposed on the arithmetic-schedule functions shows the effect of adding three extra 20-sec intervals to the schedule. From 0 to 20 sec after reinforcement, the probabilities of reinforcement for IRTs up to 20 sec long become almost as high

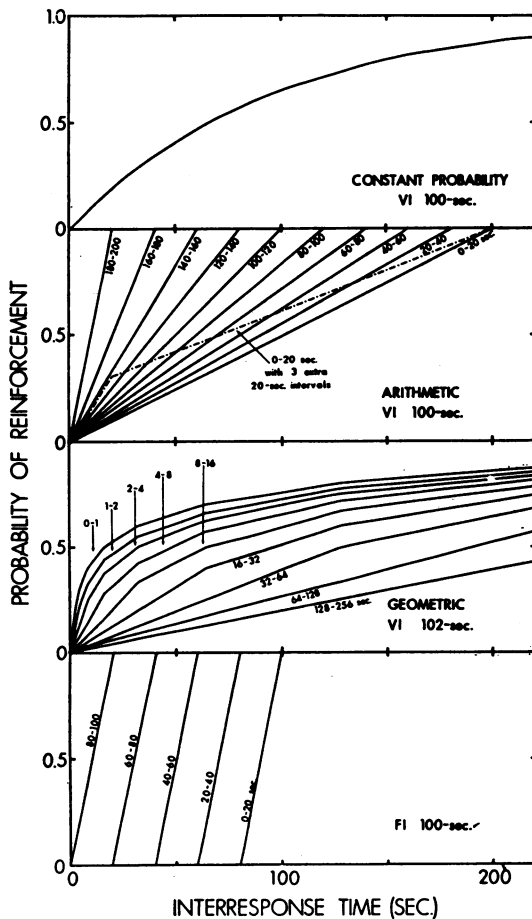


Fig. 27. Probability of reinforcement as a function of interresponse time, with periods of time since reinforcement as a parameter, in four different interval schedules: constant-probability, arithmetic, and geometric VI schedules and an FI schedule. The dotted line in the second frame shows the effect of adding extra short intervals to the arithmetic VI schedule. Details in text.

as the later probabilities of reinforcement for these IRTs within the period from 140 to 160 sec after reinforcement.

In the geometric schedule, the functions for most periods of time since reinforcement are concave downward, and are lower the longer the time since reinforcement (the function for 256-to-512 sec, omitted from Fig. 27, is a straight line; up to an IRT of 128 sec, it corresponds to the function for 32-to-64 sec). In general, the probability of reinforcement for a given IRT decreases as time passes since reinforcement, or the IRT reinforced with a given probability becomes longer as time passes since reinforcement.

For successive 20-sec periods of time since reinforcement in an FI 100-sec schedule, the functions are linear and parallel. Within the first 20 sec after reinforcement, for example, the probability of reinforcement is 0 for all IRTs of less than 80 sec. The probability then rises linearly to 1.0 for an IRT of 100 sec (cf. Morse, 1966, Fig. 3 and 4, pp. 70-71).

The schedules in Fig. 27 are illustrative, but the directions of change in the probabilities of reinforcement for IRTs as time passes since reinforcement are characteristic of the four classes of interval schedules. The choice of the periods of time over which probabilities were calculated was based in part on ease of computation, but also the further subdivision of periods of time within the arithmetic and geometric schedules would have produced functions in which the probability of reinforcement was zero for some range of IRTs. In the geometric schedule, for example, the subdivision of 128-to-256 sec into two equal periods would have produced a function in which, for 128-to-192 sec, the probability of reinforcement was zero for all IRTs less than 64 sec. This schedule, however, would probably maintain responding at a moderate rate throughout this period of time.

The problem of choosing periods of time over which probabilities of reinforcement can be calculated for IRTs is analogous to the problem of choosing periods of time within which to calculate local rates of reinforcement (Discussions, Exp. 3 and 6). The similarity of the two problems is illustrated by their common concern with the earliest times since reinforcement, but the treatment in terms of IRTs has the advantage that the difficulty can be related to an observed discrepancy between assumptions and data. Probabilities of reinforcement for IRTs are based on the assumption of a uniform distribution of starting times for each IRT, but local rates of responding, and therefore IRTs, are changing most rapidly during the earliest times after reinforcement (see Exp. 2 and 3). Thus, the difference between probabilities of reinforcement for IRTs, in Fig. 27, and recorded relative frequencies of reinforced IRTs, from a performance, is likely to be greatest at the earliest times since reinforcement (e.g., 0-to-20 sec in the arithmetic schedule in Fig. 27). Another advantage of the treatment in terms of IRTs is that no assump-

tion is made that the rate of responding at one opportunity is high enough to produce an available reinforcement before the time is reached for the next opportunity (see Exp. 3).

In any case, if IRTs become shorter and rates of responding increase as the probabilities of reinforcement for IRTs increase, then the functions in Fig. 27 agree in a general way with the performances maintained by each schedule (Exp. 3): in a constant-probability VI schedule, local rate of responding remains roughly constant over time since reinforcement; in an arithmetic VI schedule, local rate of responding increases but the addition of extra short intervals produces a relatively high local rate shortly after reinforcement; in a geometric VI schedule, local rate of responding decreases; and in an FI schedule, local rate of responding increases and very long IRTs often occur early in the interval.

The Relationship Between Observed Rates of Responding and the Probabilities of Reinforcement for Interresponse Times

Interresponse times and rate of responding are reciprocally related. For each overall and local rate of responding, there is a corresponding average IRT. The relationship between overall and local rates of responding, therefore, can be expressed in terms of average IRTs. In Exp. 3, overall rates of responding maintained by different overall rates of reinforcement in arithmetic VI schedules were compared with local rates of responding maintained by different local rates of reinforcement within intervals of various VI schedules (Fig. 15). Figure 28 illustrates three procedures for making this comparison, with the data from Pigeon 118 (Fig. 1, Exp. 1) as an example.

The top frame of Fig. 28 shows the procedure used to derive the open circles in Fig. 15, Exp. 3. The data, average overall rates of responding obtained at each overall rate of reinforcement, were connected by straight lines, the function was extrapolated linearly to zero, and rates of responding corresponding to particular rates of reinforcement were read directly from the graph, as illustrated. The middle frame shows the same procedure, except that the ordinate has been converted

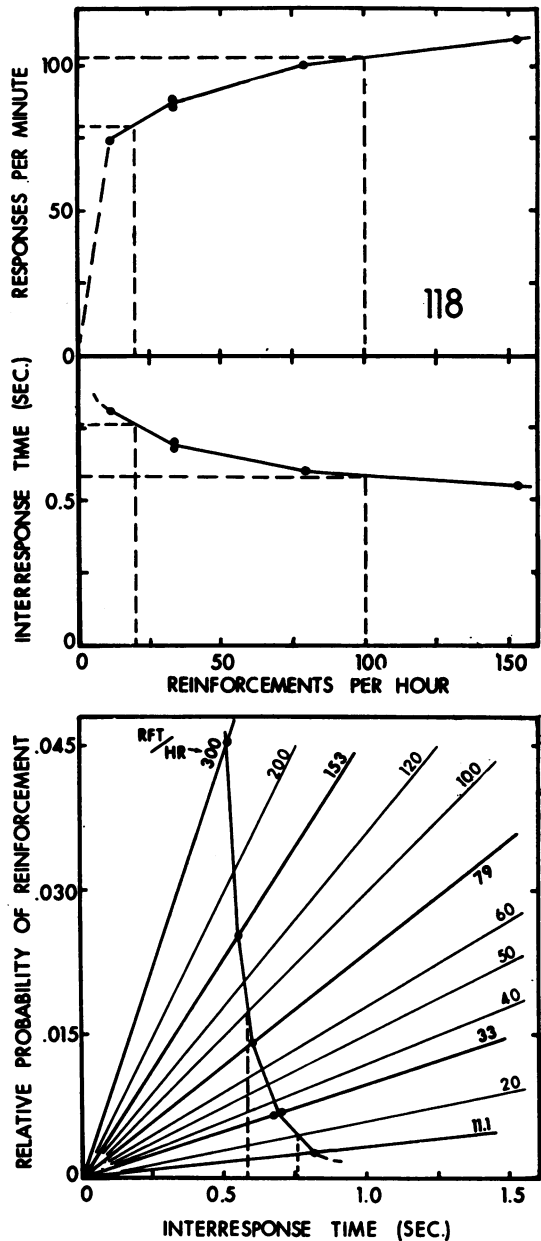


Fig. 28. Data from Pigeon 118 (Fig. 1) are replotted to illustrate three techniques for estimating local rates of responding in VI schedules. Dotted lines show estimations from 20 and 100 reinforcements per hour (rft/hr). Details in text.

from rate of responding to average IRT. Although average IRTs corresponding to different rates of reinforcement can be read directly from the graph, the abscissa does not lend itself to comparison with the probability-of-reinforcement functions for IRTs in Fig. 27.

The bottom frame of Fig. 28 illustrates a procedure that makes this comparison possible. Each of the straight lines, with overall rate of reinforcement (rft/hr) as a parameter, represents the probabilities of reinforcement for IRTs within a particular arithmetic VI schedule. The figure represents the schedules for Pigeon 118 in Exp. 1 (heavy lines) and a sample of other schedules (light lines). The functions are linear because longer IRTs are excluded; specifically, none of the functions extends beyond an IRT equal to the shortest non-0-sec interval in that VI schedule. A change in the overall rate of reinforcement provided by the schedule produces a corresponding change in the slope of the function. For example, when the overall rate of reinforcement is doubled (e.g., 20 to 40 rft/hr), the slope doubles.

The data for Pigeon 118 are plotted as intersections of the probability-of-reinforcement function for a given schedule and the average IRT maintained by that schedule. When the data are connected by straight lines, the average IRT maintained by other arithmetic VI schedules can be read from the graph, as illustrated for schedules providing 20 and 100 rft/hr. In addition, the average IRT at a particular time since reinforcement in a given schedule can be compared with the average IRT maintained by a given overall rate of reinforcement by superimposing the data function for Pigeon 118 in the lower frame of Fig. 28 on the appropriate probability-of-reinforcement functions, such as those in Fig. 27, for different times since reinforcement in a particular schedule.

The results of such a procedure, with respect to both general relationships and individual differences, do not differ much from the other two procedures, after average IRTs are converted to rates of responding. The major deviations are in those instances in which it is necessary to extrapolate beyond the range of the overall rates of reinforcement arranged for a given pigeon (cf. Pigeon 278, Fig. 15). In other words, the deficiencies of the analysis in terms of local rates of reinforcement (e.g., the problem of the earliest times after reinforcement) are not eliminated when the analysis is carried out in terms of the probabilities of reinforcement for IRTs. Nevertheless, the extent to which the deficiencies in the IRT analysis can be related to

oversimplifications in the underlying assumptions (in particular, that of a uniform distribution of starting times of IRTs) suggests that the IRT analysis can serve as a useful and perhaps a preferable alternative to the analysis in terms of local rates of reinforcement. In addition, data are available on the form of the distribution of IRTs maintained by VI schedules (e.g., Anger, 1956; Farmer, 1963), and, although the average IRT does not provide information about the shape of the IRT distribution, the relationship between rates of responding and IRT distributions is more likely to be clarified if both are expressed in the same dimension, as IRTs.

Implications of Interresponse-Time Analyses

The data function in the bottom frame of Fig. 28 shows that the average IRT decreases as the slope of the probability-of-reinforcement function increases. The average IRT, however, does not change in such a way that its probability of reinforcement remains constant (Morse and Herrnstein, 1955); the probability of reinforcement increases as the average IRT decreases (e.g., from the point on the 33-rft/hr function in Fig. 28 to that on the 79-rft/hr function). It appears that the function, if extrapolated, would asymptotically approach a probability of 0 with increasing IRT, and would reach a finite IRT at a probability of 1.0 (paradoxically, this probability corresponds to a schedule of continuous reinforcement, in which, according to the present account, latencies but no IRTs can occur).

The higher probabilities of reinforcement at which shorter average IRTs are maintained suggest some sort of reciprocal relationship between reinforcement and IRTs. Reinforcement increases responding, and therefore shortens IRTs. Other effects, perhaps including effort and fatigue, decrease responding and therefore lengthen IRTs. Such an account has considerable precedent: in balancing these two opposing factors, the pigeon appears to compromise between obeying the Law of Effect and obeying the Law of Least Effort.

A number of factors, however, may operate to shorten or lengthen IRTs. To speak simply of a reinforced IRT is convenient, but reinforcement has several effects, and some may be antagonistic. The fundamental effect

of reinforcement, and its defining characteristic, is that it enhances the organism's tendency to emit the reinforced response. Reinforcement of responses, regardless of their associated IRTs, tends to shorten IRTs (such phenomena as the high frequencies of short IRTs in DRL performances, *e.g.*, Staddon, 1965, may be an example of this effect of reinforcement).

The tendency for IRTs to shorten even in schedules of reinforcement in which long IRTs are differentially reinforced (*e.g.*, VI schedules: Anger, 1956) has prompted the suggestion that short IRTs are more susceptible to reinforcement than long IRTs (Millenson, 1966). This view seems contradicted by the fact that, in Fig. 28, shorter average IRTs are maintained only at higher probabilities of reinforcement. An alternative account of the tendency for IRTs to shorten is based on another characteristic of reinforcement, its effectiveness even after a delay (*cf.* Dews, 1960). For example, consider the effect of reinforcement of a 10-sec IRT, and compare it with the effect of the reinforcement of the last of five 2-sec IRTs. In both cases, a response at the end of a 10-sec period of time is followed by immediate reinforcement. In the former case, however, one other response is reinforced incidentally with a delay of 10 sec, whereas in the latter case, five other responses are reinforced incidentally with delays of 10, 8, 6, 4, and 2 sec. It seems reasonable to assume that the reinforcement of more responses within a fixed period of time, even though the reinforcement of some responses is both delayed and incidental, will be more likely to increase subsequent responding or, in other words, to shorten IRTs. (This characteristic of reinforcement may be relevant to the development of short IRTs in other schedules that do not differentially reinforce short IRTs, such as concurrent DRL schedules: Malott and Cumming, 1964, 1966; ratio schedules: Millenson, 1966; and stochastic schedules: Weiss and Laties, 1964; Blough, 1966).

Another factor that may tend to shorten IRTs is that long IRTs can produce decreases in the overall rate of reinforcement. When reinforcements are made available during long IRTs, the long IRTs add to the minimum interreinforcement interval. In most interval schedules, however, this factor

is usually negligible (except perhaps during acquisition), because the difference between the minimum and the actual interreinforcement intervals is likely to be small.

The lengthening of IRTs may depend on such potential factors as effort or fatigue, but reinforcement itself may also contribute. In interval schedules, reinforcement favors long IRTs because the probability of reinforcement increases with IRT. To the extent that the temporal spacing of responses comes under the control of differential reinforcement, IRTs lengthen and, as a consequence, the number of responses per reinforcement also decreases. The complication is that when reinforced IRTs are long, the tendency of reinforcement to shorten IRTs antagonizes the effects of the differential reinforcement of long IRTs. (This complication arises more obviously in DRL performances, in which IRTs too short for reinforcement sometimes preponderate.)

The final interval-schedule performance may emerge as a compromise between antagonistic effects of reinforcement. Reinforcement tends to shorten IRTs, directly and perhaps through an effect of delay of reinforcement. It also tends to lengthen IRTs, through the control produced by the higher probability of reinforcement for long IRTs. As IRTs become longer or shorter, one or the other effect of reinforcement may predominate, but the interaction that comes about because IRTs and their probabilities of reinforcement covary in interval schedules generates a balance between the effects that is reflected in the average IRT maintained for a given pigeon at a given time within a given schedule.

This analysis of the performances maintained by interval schedules of reinforcement treats them in terms of a process: the interaction of IRTs and their probabilities of reinforcement as a function of time since reinforcement. The analysis emphasizes the variables that come into direct contact with behavior, rather than the variables specified in the arrangement of schedules (*cf.* Schoenfeld, Cumming, and Hearst, 1956). According to this analysis, the power of positive reinforcement lies in its capacity to control not only the occurrence of responses, but also their temporal relationship to other responses and to events such as reinforcement. These temporal constraints, imposed on perform-

ance because the differential reinforcement of IRTs is different within each schedule and at different times within the same schedule, may bear on the relative insensitivity of interval-schedule performances to some variables (*e.g.*, magnitude of reinforcement: Catania, 1963*b*). Sensitivity to such variables is more likely to be obtained with nontemporal measures of performance (*e.g.*, the proportion of changeovers from one interval schedule to another when the schedules operate concurrently: Catania, 1966).

Schedules can be designed either to minimize or to maximize temporal constraints (*cf.* "synthetic" VI schedules, Newman and Anger, 1954; stochastic reinforcement of IRTs, Weiss and Laties, 1964; reinforcement of "least-frequent" IRTs, Blough, 1966), but eliminating or establishing constraints with respect to some variables is bound to affect constraints with respect to others. In other words, no particular schedule of reinforcement manipulates "response strength"; rather, it controls a particular sample of the various properties of responding.

APPENDIX II: CONSTANT-PROBABILITY VARIABLE-INTERVAL SCHEDULES

A constant-probability VI schedule is one with a minimal correlation between probability of reinforcement and the time since the last reinforcement. In other words, a constant-probability VI schedule provides that time since reinforcement cannot acquire discriminative control over responding through its relationship to the availability of subsequent reinforcement. This condition may be a prerequisite for local rates of responding that do not change with the passage of time since reinforcement. The condition is obviously not satisfied by an FI schedule, which makes reinforcement available at the same time in every interval; it is also not satisfied by a variety of standard VI schedules, including the arithmetic and the geometric (Exp. 3). The present section considers the design of constant-probability VI schedules, a problem significant for the technology of behavior because a constant rate of responding provides a useful baseline against which to assess the effects of many variables.

Two methods of designing constant-probability VI schedules will be considered. One, illustrated by the random-interval schedules of Farmer (1963) and Millenson (1963) and by the constant-probability schedule of Exp. 3, holds constant the separation in time of successive opportunities for reinforcement while varying the relative frequencies of different intervals. The other, illustrated by the schedules of Fleshler and Hoffman (1962: see Exp. 3, Discussion) and by a modified schedule described below, holds constant the relative frequencies of the different intervals while varying the separation in time of successive opportunities for reinforcement.

The random-interval schedules of Farmer and Millenson arranged a constant, recycling time interval, *T*. Within each *T*-sec interval, the first response was reinforced with a probability, *P*, corresponding to the statistic, reinforcements per opportunity. The timing of the *T*-sec intervals was not interrupted during reinforcement, so that a 0-sec interval (reinforcement of the first response after a reinforcement) was possible if *T* was less than the duration of reinforcement. As arranged by Farmer, the schedules also included a limited hold: a reinforcement made available within one *T*-sec interval was not kept available beyond the end of that interval.

Farmer studied a range of *T* from 1 to 60 sec, and a range of *P* from 0.0052 to 1.0 (when *P* equaled 1.0, these schedules corresponded to FI schedules). Cumulative records showed that rate of responding was roughly constant over time since reinforcement at only some combinations of *T* and *P*. The deviations can be attributed to at least three factors: the limited hold, particularly when *T* equaled 1 sec; the time to the first opportunity for reinforcement when *T* was large (30 or 60 sec), which produced long pauses after reinforcement (*cf.* constant-probability VI 379-sec for Pigeon 278 in Fig. 11, Exp. 3); and, trivially, the FI character of the schedules when *P* equaled 1.0.

Millenson chose 4 sec as an optimal value of *T*, and arranged schedules with *P* equal to 0.0667 and 0.0183. In cumulative records, local rates of responding appeared roughly constant over time since reinforcement, although one of three pigeons showed systematically low rates of responding for some time after reinforcement when *P* equaled 0.0667, and

all three pigeons showed cyclic short-term alternations between high and low rates when P equaled 0.0183.

The average rate of reinforcement in a random-interval schedule equals P/T . As P and T become small (see Millenson, 1963), the distribution of interreinforcement intervals approaches the exponential distribution:

$$f(t) = \frac{e^{-(t/\bar{t})}}{\bar{t}} dt,$$

where t is the duration of an interval, $f(t)$ is the relative frequency of the interval, \bar{t} is the mean interval, and e is the base of natural logarithms. The relative frequencies of the discrete intervals in the following distribution with T equal to 10 sec and P equal to 0.10 provide one approximation to the continuous distribution described by the equation (intervals are shown in parentheses): 0.100 (10-sec), 0.090 (20-sec), 0.081 (30-sec), 0.073 (40-sec), 0.066 (50-sec), 0.059 (60-sec), 0.053 (70-sec), 0.048 (80-sec), 0.043 (90-sec), 0.039 (100-sec), and so on. In this sequence, the exact relative frequency of t_n , the n th interval with intervals ranked in order of duration, equals $P(1-P)^{n-1}$.

The constant probability schedule of Exp. 3 provided a distribution of intervals similar to the distribution with P equal to 0.10 in the random-interval schedules of Farmer and Millenson. Each interval was an integral multiple of the minimum interval, t (see Table 2 and Fig. 11, Exp. 3). The schedule differed from the random-interval schedules in that the sequence of intervals within each session was predetermined by a punched tape. Consequently, the schedule specified a longest interval at the end of which the probability of reinforcement necessarily became 1.0.

Both the random and predetermined methods of arranging constant-probability schedules have certain advantages. In a random-interval schedule, an interval of any multiple of T -sec is possible, though less likely the larger the multiple. The probability of reinforcement never becomes 1.0 except in the *ex post facto* sense that there will always have been a longest interval when the relative frequencies of different intervals are tabulated at the end of a particular session.

Under some circumstances, however, a predetermined sequence of intervals may be preferable to a randomly generated sequence. A

random generator will occasionally (and unpredictably) produce a long, locally regular sequence, which, through a temporary local effect on the rate of reinforcement or on the correlation between reinforcements and time since reinforcement, may have significant effects on performance, especially if it occurs in the early stages of acquisition. A predetermined sequence (for example, in the form of a loop of punched tape) not only avoids this possibility, but also may simplify data collection because the experimenter can predict the number of times the organism will reach various times since reinforcement within a particular experimental session.

A satisfactory sequence of intervals in which each interval is an integral multiple of the minimum interval, however, is necessarily long (e.g., the 60-interval sequence in Table 2). With the usual VI programmer (e.g., Ralph Gerbrands Co.), such a sequence requires excessively long tapes and produces the problem of tape breakage and tangling. A desirable sequence for many applications, therefore, would be short and yet would retain the basic characteristics of a constant-probability VI schedule.

The method proposed by Fleshler and Hoffman (1962) for generating a sequence of intervals roughly satisfies these requirements. Their progression of intervals is described by the equation:

$$t_n = \bar{t} [1 + \ln N + (N-n) \ln (N-n) - (N-n+1) \ln (N-n+1)],$$

where t_n and \bar{t} are, again, the durations of the n th and the mean intervals respectively, N is the total number of intervals, and \ln represents the natural (base e) logarithm. The equation is derived from the exponential distribution (cf. Discussion, Exp. 3). In effect, as the probability of reinforcement increases from one opportunity to the next (Fig. 14), the temporal separation of successive opportunities increases in such a way that the probability of reinforcement per unit of time (in other words, the local rate of reinforcement) remains roughly constant. In discussing the problem that this distribution provides reinforcement at discrete points in time and the probability of reinforcement at other times is zero, Fleshler and Hoffman state:

"This difficulty would be insurmountable if organisms had perfect temporal

discrimination. The fact that they do not means that the effects of rf [reinforcement] at a given point in time will spread to nearby points in time (at least within the difference limen). If the differences between successive terms in the progression were sufficiently small so that within the schedule context, discrimination between these terms were poor, the effective probability distribution would be continuous and would approximate the theoretical distribution" (Fleshler and Hoffman, 1962, p. 530).

This schedule, as arranged by Chorney (1960), maintained a relatively constant local rate of responding over most of the range of time since reinforcement, thus supporting the assumption that this and the preceding constant-probability VI schedules are equivalent and demonstrating the importance of the separation of different opportunities for reinforcement along the continuum of time since reinforcement. Chorney's finding of a higher rate of responding shortly after reinforcement than later within intervals, however, prompts a detailed examination of the early terms of the progression.

A sample sequence of intervals from the progression is the following (20 intervals, mean = 100 sec): 2.5, 7.7, 13.5, 19.3, 25.5, 32.2, 39.3, 47.0, 55.5, 64.5, 74.5, 85.6, 98.2, 112.5, 129.2, 149.4, 174.6, 208.6, 260.9, and 399.6 sec. Local rates of reinforcement are approximately one reinforcement per 100 sec at all opportunities except the first (2.5 sec, at which local rate of reinforcement is about 35% higher) and the last (399.6 sec, at which local rate of reinforcement is about 30% lower). The relatively high, early local rate of reinforcement might account for Chorney's finding, but this deviation alone cannot be taken too seriously because the computation of local rates of reinforcement is most arbitrary at early and late times after reinforcement.

The progression can also be evaluated in terms of interresponse times. Consider a 2.5-sec IRT that begins either within the first 2.5 sec after reinforcement or between 2.5 and 7.7 sec. If the IRT begins within 2.5 sec, its probability of reinforcement is 0.050 because it must end at least 2.5 sec after reinforcement and because reinforcement is arranged

at this time in one of every 20 intervals. If this IRT begins between 2.5 and 7.7 sec, however, its probability of reinforcement is 0.053 (reinforcement at 7.7 sec in one of 19 intervals) multiplied by the probability of 0.48 that the IRT will end after 7.7 sec (see Appendix I). This probability equals 0.0252, or about half the earlier probability, and the probability remains at roughly this value through most of the remaining time since reinforcement. In light of Chorney's findings, therefore, its higher value shortly after reinforcement may be significant. The modification suggested below provides a progression similar to Fleshler and Hoffman's, but takes into account the probabilities of reinforcement for IRTs at different times since reinforcement.

In a sequence of intervals such that all intervals occur with the same relative frequency, the probability of reinforcement at the end of a given interval, t_n , is given by the reciprocal of the number of intervals equal to or greater than t_n ; that is to say, reinforcements per opportunity grows with time since reinforcement as the reciprocal of the number of intervals ending at or after the given time since reinforcement. But given that a particular IRT is shorter than the time between successive opportunities, the probability of reinforcement of the IRT is directly proportional to reinforcements per opportunity (see Appendix I). Thus, to hold constant the probability of reinforcement for a given IRT, the increments in the durations of successive intervals in the progression must grow directly with reinforcements per opportunity.

For example, in a progression of 20 intervals, the probability of reinforcement at the end of the shortest interval, t_1 , is 0.050, and so the probability of reinforcement for an IRT of t_1 -sec is also 0.050. But the probability of reinforcement (rft/op) at t_2 , at the end of the next shortest interval, is 0.053 (1/19). The duration of the increment added to t_1 , therefore, must be 1.053 (20/19) times t_1 if the probability of reinforcement for this IRT at t_2 is to be held equal to 0.050. Correspondingly, the increment added to t_2 must be 1.056 (19/18) times t_1 , and so on. A general progression that satisfies these requirements and so holds constant the probability of reinforcement for any IRT less than or equal to t_1 sec is:

$$t_n = \sum_{i=1}^n \frac{\bar{t}}{(N+1)-i},$$

where the symbols are the same as those in the Fleshler and Hoffman equation. The following sequence of 20 intervals with a mean of 100 sec is an example of the progression: 5.0, 10.3, 15.8, 21.7, 28.0, 34.6, 41.8, 49.4, 57.8, 66.9, 76.9, 88.0, 100.5, 114.8, 131.4, 151.4, 176.4, 209.8, 259.8, and 359.8 sec. This progression, with a shortest interval longer than that in the Fleshler and Hoffman progression, is likely to generate relatively lower rates of responding shortly after reinforcement than were observed in Chorney's experiment.

With the qualification of a uniform distribution of starting times for a particular IRT (see Appendix I), the sequence holds exactly constant the probability of reinforcement for any IRT less than or equal to the duration of the shortest interval. The sequence also incidentally holds local rates of reinforcement roughly constant at one reinforcement per 100 sec, with the sole exception of the last opportunity (end of the longest interval), when the local rate of reinforcement is higher.

In practice, the performances maintained by the Fleshler and Hoffman schedule and by the present modification would probably not be appreciably different at any but the shortest times after reinforcement. Both schedules, as short sequences with the approximate characteristics of constant-probability VI schedules, have been in laboratory use and, on inspection of cumulative records, appear to maintain fairly constant local rates of responding over most of the range of time since reinforcement.

Additional study may suggest further refinement of the schedules. For example, if the earliest times after reinforcement have special characteristics, it may be desirable to find out whether a 0-sec interval could be included in the sequence without excessively raising the local rate of responding shortly after reinforcement (see Exp. 2).

The above progressions provide no information about the maximally effective order of the intervals that make up a constant-probability VI schedule. Sequential properties can produce systematic local changes in the rate of responding. For example, if short intervals are always followed by long intervals, the local rate of responding may become

relatively low immediately after reinforcement at the end of a short interval. Only informal data on the effects of the order of intervals are available. One schedule (colloquially, *the golden tape*) was developed over a period of years by several investigators at the Harvard Pigeon Laboratories. One feature that persisted among several variations in the schedule was that the two shortest intervals were separated by exactly two of the intermediate intervals. One version of the schedule is the following (15 intervals, mean of 180 sec): 560, 60, 220, 5, 140, 120, 5, 260, 500, 60, 300, 20, 60, 350, and 140 sec. The order of the intervals was assumed to contribute to the schedule's success in maintaining roughly constant local rates of responding with only minor sequential effects (as observed in cumulative records). It is interesting to note that this schedule and a similar one designed by Anger (1956) had the property that local rates of reinforcement at successive opportunities, though not constant, varied considerably less than in arithmetic or geometric VI schedules.

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Received 10 June 1963.